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Closed loop control of a telemanipulator such as is used for telesurgery is intolerant to loop time delay of more than 0.05 second. Such a system goes unstable, especially when force feedback is employed. The time delay inherent in modern high-bandwidth communication channels such as satellite or ISDN telephone systems is mostly attributable to required modulation/demodulation time, and can easily exceed 0.5 second.

(I) This research applies a new approach, called *fuzzy sliding control*, to smooth out and stabilize teleoperation with time delay in the force and visual feedback. A demonstration system was built and fuzzy sliding control was evaluated relative to other control methods operating under time delay. While still not a perfect solution, it provided better stabilization than other methods.

(II) This research tests the hypothesis that if video signals must be delayed due to modulation/demodulation as required by the channel, it may be better to send control signals by a faster method if possible, even if that means force feedback will not arrive in synchrony with vision or audio feedback. Experimental trials of various laparoscopic telesurgical tasks were performed with the surgeon remote from the patient and a paramedical assistant local to the patient. Results clearly showed that whenever the remote surgeon operated laparoscopic instruments (as compared to adjusting the laparoscope and letting the assistant do the actual surgery) the asynchronous feedback was better.

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Thomas B Sheridan — Jan 25, 1998

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PART I

STABLE FORCE REFLECTING CONTROL WITH TIME DELAY

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Chapter 1

Introduction

1.1 Telerobotic Surgery

With the development of modern technologies (including remote sensing, robotics, medical informatics, telepresence, supercomputing, digital image processing and telecommunications), telemedicine has become a very active research area in the 1990s. The original idea of telemedicine was to provide medical care over long distance through the use of telecommunications. In the early days of the 1960s, the primary target was to implement telediagnoses [Sheridan, 1992]. Now efforts are underway in the world to develop telesurgery, where a surgeon operates, by means of a telerobotic device and a communications link, on a patient who is an arbitrary distance away. The current goal in the U.S.A. is the development of a telerobotic surgical system that will assist a medical care provider (who might have limited medical care experience) in the management of a medical emergency (including surgical intervention) at a location that is remote from the hospital and the experts available there. Such an event might occur in both civilian and non-civilian situations in locations such as remote rural areas, ships at sea, battle fields, natural disasters, research stations in the Antarctic, and NASA space missions, among others.

Telesurgery is a special application of teleoperation that requires good telerobotic devices to perform the remote operations and a good quality of telepresence (visual, audio, and haptic feedback) to enhance the surgeon's medical performance. So far the research projects on telesurgery have had different focuses, such as surgical telerobot design, surgical tool settings, telepresence surgery, etc. Experiments on surgical telerobotics from 1992 until today have evolved considerably [Kanade et al 1994]. Green[1992,1995], at SRI International in California, has developed an advanced telesurgery system, which is a two armed, five degree of freedom, bilateral force reflecting telerobotic system. Through the demonstration (called as Telepresence Laparoscopic Surgery) in Washington, D.C. at the annual convention of the Association of the U.S. Army, in 1994, SRI established that precise surgical procedures can be carried out with telepresence. In 1994 another group at Johns Hopkins Bayview Medical Center conducted an experiment on telerobotic laparoscopic surgery for the purpose of assessing the feasibility of telerobotic assisted surgery [Kavoussi, 1994]. These experiments did not involve significant time delay.

The first experiment of telerobotic surgery in the world was carried out between the NASA Jet Propulsion Laboratory in Pasadena, California, and the Telerobotic Laboratory of the Politenico di Milano, Italy on July 7,1993 [Rovetta,1996]. During that experiment, an Italian robot in Milan was remotely controlled by an Italian surgeon in the United States. The surgical operation involved the execution of a biopsy, aspiration of organic material, and two incisions in preparation of laparoscopy. Transmission was effected by means of a double satellite link, with three transceiver stations: one in Italy, one close to New York, and one in Pasadena, and two geostationary satellites, the first over the Atlantic and the second over the United States. The route length of the signals was 150,000 km in each direction and the transmission delay time was significant (1.2 seconds) on the satellite network. To increase safety and system reliability, an optical fiber network with ISDN located on the ground and on the sea bed was used to obtain a parallel signal transmission with fast transmission rate. This experiment showed that the time delay in telerobotics should always be taken into consideration so that surgical telerobotics can be safely applied in those operations where time interaction is kept under control (e.g. in biopsies and incisions under anesthesia). While these experiments involved time delay, they did not involve force feedback in the telerobotic systems.

Sheridan [1994] suggested to perform telesurgery by using the available intelligence and assistive dexterity in the form of a paramedic (or in some cases an untrained assistant) available locally to the patient, which suggests a more acceptable application of telesurgery in the future. Hence cooperative manipulation (supervisory control) between a paramedic local to the patient and a surgeon through a telerobot becomes an important issue in telesurgery in the scientific sense. Besides, time delay effects in telesurgery, which degrade the quality of telepresence (visual, audio, and force feedback) are indeed a very important issue.

Previous experiments on telesurgery have not paid much attention to the combination of time delay and telepresence (especially force feedback). In this thesis, teleoperation including force feedback with time delay (which is called stable force reflecting control with time delay) will be addressed.

1.2 Telepresence in Telesurgery

Telesurgery is a natural extension of developments in teleoperation, where the latter is defined as "the extension of human inspection and manipulation capability to remote or otherwise inaccessible locations"[Sheridan, 1996]. A telerobot is a device that has sensors (such as video camera) and actuators (hands for grasping and arms for positioning and

conveying forces to the hands, plus some means of mobility), which are combined with a means of communicating information to and from the human operator. Usually, a complete telerobotic system consists of master-slave robotic manipulators, communication link, remote sensing devices (including video, audio, and force feedback etc.) (Figure 1-1).

Figure 1-1: Block diagram of a telerobotic system

In most telerobotic systems, human operators control the endpoint of the master manipulator (robot), which, in turn, determines the joint angles of the master and the slave manipulators. In a force-reflecting teleoperator system, the reaction force sustained by the slave is fed back and reconstructed by the master manipulator to provide the operator a sense of what he would feel if he were handling the task directly. The kinesthetic coupling between the human operator and the task is part of the currently accepted idea of "telepresence" which implies feeding back all sensory information and energy, including vision, sound, smell, force, tactility etc., such that the human operator feels physically present at the remote site.

1.2.1 Telepresence for better operation

Telepresence is commonly claimed to be important for direct manual telemanipulation. It has yet to be shown how important is the sense of "feeling present" *per se* is to performance as compared to simply having high resolution, a wide field of view and other attributes of good sensory feedback [Sheridan, 1992]. Generally speaking, telepresence can be classified as visual telepresence, auditory telepresence (binaural localization and spectral correspondence to the real world), force (muscle force) telepresence, and tactile (skin sense) telepresence.

The quality of telepresence has direct effects on the performance of teleoperation. From the experience that a force-reflecting teleoperator system performs better than a system without force feedback one can understand the concept of telepresence partly. It is intuitively assumed that the performance of a remote manipulator will rival direct manual operation if the operator is presented with all sensory information of the remote site and if the remote manipulator has the same dexterity as a human arm (or hand). Presumably under

such circumstances, the human operator can feel as if he is at the remote site and is performing the operation directly.

However, the concept of "to feel as if at the remote site" is far beyond the necessary requirement of the original purpose of using teleoperation systems to perform tasks in an inaccessible location. For example, in a combat environment the operator might be subject to a high level of stress and anxiety if he were presented with the realistic reconstruction of the force, sound, smell and sights of the battle field. In such cases, "to feel as if at the remote site" is not appropriate since the operator will suffer both physically and mentally from the hazardous environment [Blais & Lyons,1988]. On the other hand, selected and modified feedback may reduce the stress of fatigue associated with a task and increase the performance level. Since "to feel as if at the remote site" is not always helpful in teleoperation, the ideal telepresence should not be to feed back all sensory information and energy of the remote site the operator, but should be to feed back such information and energy as will increase the performance level, but not such information and energy that will jeopardize the operation. In conclusion, teleoperation should be a means to achieve higher performance with necessary remote information, but not an end in itself.

Force reflection, considered as a subset of telepresence, has been shown to be beneficial in remote constrained motion tasks [Sheridan, 1992]. Task completion time is often reduced by as much as 40 percent when the operator is given force feedback information. Even with visual feedback, human performance in terms of task completion time is still severely limited unless the operator is supplied with force feedback. Therefore, force reflection capability has been considered necessary for a high performance teleoperator system. However, exact force reflection, just like other items that constitute telepresence is not always necessary or most helpful. The following section discusses the problems of force feedback.

1.2.2 The limits of force reflecting teleoperation

Since the human muscle-skeletal system is directly coupled to the teleoperator and task dynamics in force reflection teleoperation, the overall system dynamics becomes very complex and the performance of the overall system is very much dependent upon the human capability. Hence, the performance of the remote manipulation can be affected in several ways:

(1) A force reflection teleoperator system can be much more fatiguing than a positioning device such as a mouse or a teleoperator without force feedback. Since the operator is coupled with the task in a force reflection system, whatever force is exerted by the slave

manipulator will be reflected to the operator and sustained by the operator's muscles. Therefore, it is often fatiguing to use a force reflective teleoperator system.

(2) If the teleoperator exactly reflects the environment to the human operator (complete transparency of the interface), then the capability of the system will be exactly limited by the human operator as well. For example, the remote manipulator will not be able to lift a weight heavier than what the operator can lift directly, or execute a fine motion more precisely than what he can execute directly. Moreover, if a task requires an input bandwidth higher than what the human operator can exert, the operator will not be able to do it.

(3) The dynamics and control of a force-reflection teleoperator is very complex. The force reflection will develop a closed-loop between the human-master subsystem and the slave-task subsystem. The dynamics of a force reflection teleoperator system not only depends on the above two parts, but also depends on the transmission between the two parts. For example, the stability problems due to noise and signal transmission time delay are well acknowledged and have severely limited the remoteness of the operation [Sheridan 1992]. Because of the reflection nature of force feedback, delayed force feedback, unlike delayed visual feedback and audio feedback, could interfere with the operator's command input. Therefore, Ferrell [1966] stated that force feedback is "not only a source of information, but may act as a disturbance input as well".

To summarize, although the performance level measured by task completion time can be remarkable in certain types of tasks, a force reflecting teleoperator system is fatiguing, is limited by the dexterity and capacity of the human operator, and can be unstable and hard to control especially in the presence of time delay. Even with an ideal teleoperator system which provides a complete transparent interface between the operator and the task, the performance level is still limited by the performance level of the human himself.

1.3 Stable force reflection with time delay

1.3.1 Time delay effect on force reflection of telerobotic surgery

Several successful demonstrations of remotely controlled endoscopic surgery and laparoscopic surgery have taken place recently [Green,1995; Kavoussi,1994; Partin,1995]. However, in these demonstrations there was no appreciable time delay between the surgeon's actions and the resulting laparoscopic image or between the surgeon's actions and the force feedback. Rovetta's demonstration of telesurgery between Milan, Italy and Pasadena, CA, U.S.A. used satellite communication networks which took 1.2 seconds time delay for one-way information transmission (including video, audio, and sensing

signals) but no force feedback. In 1993, Yamashita demonstrated his teleoperation system between Tokyo, Japan and Encina, CA,U.S.A. via ISDN communication lines across the Pacific Ocean[Yamashita, 1993].The data transmission time was approximately 0.70 seconds which doesn't include the necessary time delay for image compression and decompression (minimum 0.60 seconds). The latest available technology to do video conference typically use several ISDN channels or T1 link that result in delays in the video signals of at least a half second, round trip (e.g. 0.60 seconds for the Zydacron system [Zydacron,96]). Therefore, time delays always exist in the teleoperation systems because of the constraint of the available technology.

In the case of telesurgery, (particularly where satellites and long distance ISDN lines are used) the time delays appear both in the transmission of commands to the remote surgical system and in the feedback of information (e.g. video, audio) to the surgeon. Among all the effects of time delays, such as image transmission, control signal transmission, sensing information feedback, and so on, force reflection is dominantly important to perform practical telesurgery . The latter is true because a human can ignore visual time delays of a small fraction of a second, but humans in a force loop inherently close the loop through the control handle and force feedback generating spurious movements that cannot be suppressed by the human operator without holding the control handle rigid.

The force reflection control of a teleoperation system with large time delay (more than 0.2 seconds) becomes unstable [Bejczy,1994]. Usually the communication time delay is in order of 1 second if satellite communication is used [Sheridan, 1989]. When the communication time delay become significantly large comparing with the dynamic time constants in the robotic system (e.g. time delay >0.2 seconds), the delayed forces imposed on the operator's (surgeon's) hand will be significantly out-of-phase with his or her intended motions, and will therefore excite instability in the teleoperation system and make teleoperation or telesurgery very difficult to implement. On the other hand, from a control system point of view, large time delay generates a large phase lag in the system loop, decreasing the phase margin of the system significantly and making the system unstable. It is very difficult to design a compensator for such a delay [Niemeyer and Slotine, 1991]. Therefore, the classic linear controller, such as proportional-plus-derivative (PD) control can not make the teleoperation system with large time delay stable unless some way can be found to change the system's physical parameters [Anderson, 1989]. A better way to explain the instability of force reflection of teleoperation with time delay is to apply passive theory or scattering theory, which will be described in the thesis.

1.3.2 Previous works on stable force reflecting control

Several approaches to coping with time delay in telerobotics have been proposed since the 1960s. The previous approaches can be classified into the following different types: (1) visual aiding approaches (including "move and wait" strategy, predictor display, force signal display), (2) passive control and (3) supervisory control. Ferrell [1966], Buzan [1989] and Buzan and Sheridan [1989] investigated the special case of delayed force feedback, and developed specialized predictors to cope with delayed force. Time delay in a Teleoperation loop can also be circumvented altogether by using supervisory control, in which the telerobot is programmed to perform operations in short closed loop segments and control is managed locally through artificial sensors and a computer within the task segments [Ferrell and Sheridan, 1967; Brooks, 1979; Conway et al., 1990; Funda et al. 1992; Sheridan,1992]. Hirzinger et al. [1993] demonstrated telerobotic control from the Earth to the NASA Apace Shuttle for simple manipulation tasks, making use of both predictor display and supervisory control techniques. Other investigators have suggested means of artificially damping or smoothing control signals to prevent instability which can be called a class of passive control [Raju,1986; Anderson,1988].

Raju [1986,1988] was the first to apply two-port network models to the stability analysis of teleoperators. He suggested that if the teleoperator system is designed such that its impedance characteristics can be adjusted by the human operator for different tasks, it may be possible to improve the performance level of the operator using both system characteristics equations and positive real matrices. He analyzed and solved the 'bound' of parameters for stabilizing PD-controllers against all passive environments. The stable port behavior can thus be specified using gains within the parameter bounds. Hannaford & Spong [1988] introduced a similar analysis using hybrid two-port networks.

Anderson and Spong [1988] extended the methodology of teleoperator network design with the passivity theory and the scattering matrix. Based on the passivity theorem, overall system stability is maintained by securing the passivity of each subsystem. In this way, the design process is much simplified. However, the trade-off is that the overall system becomes too conservative (more stable than needed). By designing the communication subsystem with lossless scattering matrices, Anderson and Spong also solved the stability aspect of the time delay problem. Niemeyer and Slotine [1991] presented a similar result in dealing with time-delay problems. Based on Raju's work, Chin analytically derived the design guideline for stable passive controllers [Chin, 1991].

With the inspiration of the "move and wait" strategy, and the function of the series elastic actuator [Pratt, 1995], the author proposed a novel control approach--Fuzzy Sliding Control. In this thesis, the new control approach will be described in detail.

1.4 Outline of Thesis Contents

This thesis introduces my contributions to the subject, stable force reflecting control of telerobotic surgery system with time delay. The main part of the thesis focuses on development of the new approach of Fuzzy Sliding Control and the derivation of the modified passive control approach. Both approaches have been applied in a telerobotic surgery system. This thesis is organized as follows:

Chapter 1 introduces the technologies in telerobotic surgery, time delay effects on force reflection of teleoperation and the previous work on the subject.

Chapter 2 explains why Fuzzy Sliding Control (FSC) is useful in teleoperation, what is FSC and how to design FSC.

Chapter 3 describes the system structure of FSC in telerobotic systems and the modeling of a teleoperation system, and it elaborates how FSC stabilizes the teleoperation system.

Chapter 4 presents the methodologies of passive control and supervisory control. A modified approach to passive control is proposed.

Chapter 5 describes the experimental studies on FSC by means of a virtual environment. Subjective experiments for different controllers are conducted with respect to different time delays (0-1 sec.). Both subjective and objective evaluation are described.

Chapter 6 introduces system design of a telerobotic system including hardware and software design for experimental study and surgery demonstration.

Chapter 7 presents the experimental data for different control approaches, e.g. passive control and FSC. The resulting analyses are based on the dynamics responses.

Chapter 8 summarizes this thesis and discusses the direction of future research.

Chapter 2

Theory and Design of Fuzzy Sliding Control

2.1 Intuition of force reflecting control with time delay

From our simulations and experiments, we observed that when the remote robot (slave) makes contact with the task environment, due to the delayed information feedback, the master robot excites a system oscillation (instability). This instability shows less of a repetitive pattern, but finds a self-sustaining oscillation at a frequency inversely proportional to the delay. In both cases the instability was provoked by an impulse disturbance which is associated with the slave contact with the environment, and the action of the human arm (also human arm locomotion effects) to a step function force signal.

Time delay has the following effects on the force feedback (or force telepresence).

- The human operator cannot predict exactly the instant when the slave robot contacts with the task environment;
- Once the slave contacts the task environment, the force signal in the slave during the transition period (from free motion to full contact) is roughly a step function;
- When the slave force signal (step function), which is not a smooth function is reconstructed on the master robot, the human operator will generate an impulse (force & position) disturbance.

Intuitively there are several ways to avoid instability, which are:

- Visual predictor display. Some people have already investigated this approach, which indeed improved the operation performance. However, in complex task cases, it is very difficult to achieve perfect predictor display (predicted graphics overlaid on the video image).
- Add artificial damping to the robot. This gives us an approach called passive control. Using the artificial damping factors, the energy injected by the human arm in the form of impulse force when contact takes place at the remote site can be dissipated in the master-slave global system.
- Add a "smart" filter" to smooth the contact force signal of the slave robot and feed back the steady force signals to the master robot. In the mean time, add robustness to the controllers of both slave and master robot.

For the third approach, there are some difficulties to design such a smart filter and robust controllers, because there are so many uncertainties in the telerobotic system. For example, the task environment may vary during the operations, and the operator's arm model is not

known to us even today. Without precise mathematic models, how can we design appropriate controllers for the robots ? The answer is that we can build the model from our experience and control engineer's expertise. We have already known that a series-elastic actuator can have very good stability in dealing with surface contact [Pratt, 1995]. If we can build a smart control that has adjustable stiffness and robustness, the system performance will be improved significantly. A new control ---Fuzzy Sliding Control which has the two features (smart filter, adjustable stiffness and robustness) will be introduced in the following sections.

2.2 Fuzzy Logic and Fuzzy Control

Fuzzy logic is much closer in spirit to human thinking and natural language than traditional logic. Essentially it provides an effective means of capturing the approximate, inexact nature of the real world. A fuzzy logic controller (FLC) is a set of linguistic control rules which, in combination, result in an algorithm to map quantitative inputs to quantitative outputs. The methodology of the FLC is very useful when the processes are too complex for analysis by conventional quantitative techniques or when the available source of information can only be interpreted qualitatively, inexactly, or uncertainly. Thus fuzzy logic control may be viewed as a step toward a rapprochement between conventional precise mathematical control and human-like decision making.

Here is an example of FLC with approximate inference (Mamdani's Approach) [Mamdani, 1976]. If there exist N rules in the fuzzy control system, the *i*th rule is in the form of

IF inputs $x_1 = A_i$, $x_2 = B_i$, THEN $u = C_i$.

Let x_{10}, x_{20} be the inputs of x_1, x_2 correspondingly, so the truth value of the premise (or membership) can be expressed as

$$\mu_i = \mu_{Ai}(x_{10}) \wedge \mu_{Bi}(x_{20})$$

where $\mu_{Ai}(x_{10})$ is the membership of x_{10} pertaining to fuzzy set A_i and $\mu_{Bi}(x_{20})$, membership of x_{20} pertaining to B_i, and "$\wedge$" is an operator, which can be defined as "minimum" or other fuzzy operator [Pedrycz, 1993]. Then, the membership of the control output is

$$\mu_c(z) = \bigcup_{i=1}^{N} \mu_{Ci}(z)$$

where "∨" is an operator, which can be defined as "maximum" or other operators [Pedrycz, 1993]. Therefore the output (fuzzyfication, or fuzzy decision making) can be obtained from the centroid formula.

$$u = \frac{\sum \int \mu_{Ci}(z) z dz}{\sum \int \mu_{Ci}(z) dz}$$

The inference process can be described in the following figure.

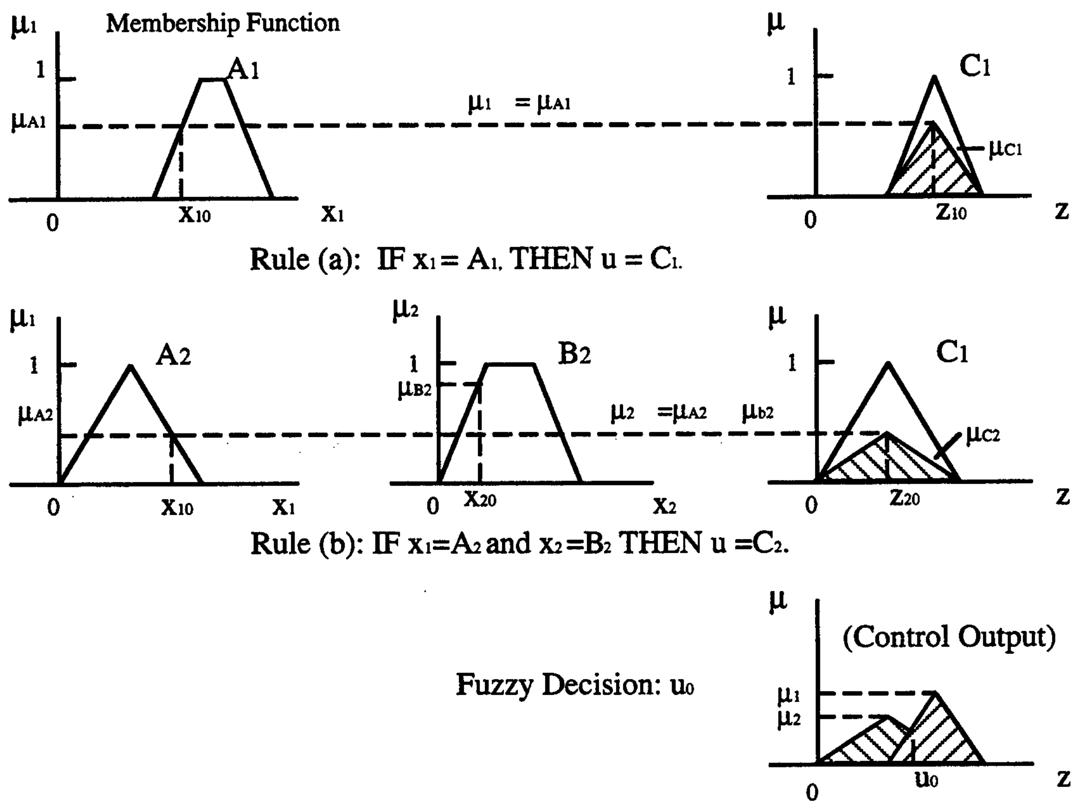


Figure 2-1: Inference process of fuzzy control

Fuzzy logic control has been applied to many industrial systems successfully since Mamdani's pioneering work in 1976 [Mamdani, 1976]. As a heuristic approach, fuzzy logic control is usually based on expert knowledge. For an ill-defined and complex system, fuzzy control has advantages over the traditional approach because it is not necessary to do the mathematic modelling. On the other hand, it is suitable for human knowledge interfacing because of linguistic flexibility. Although fuzzy control is very successful, especially for the

control of nonlinear systems, there is a lack of appropriate design technique with regard to the control performance and stability of systems. For example, fuzzy control is rule based, and the rules chosen by the human experts may vary for a given system plant. The tuning of the rule base is done in a trial and error manner. There is no consistent methodology to guide fuzzy partition, rule-tuning, and approximate fuzzy inference, so that necessary system performance and stability can be achieved. Figure 2-2 shows a standard structure of fuzzy control system.

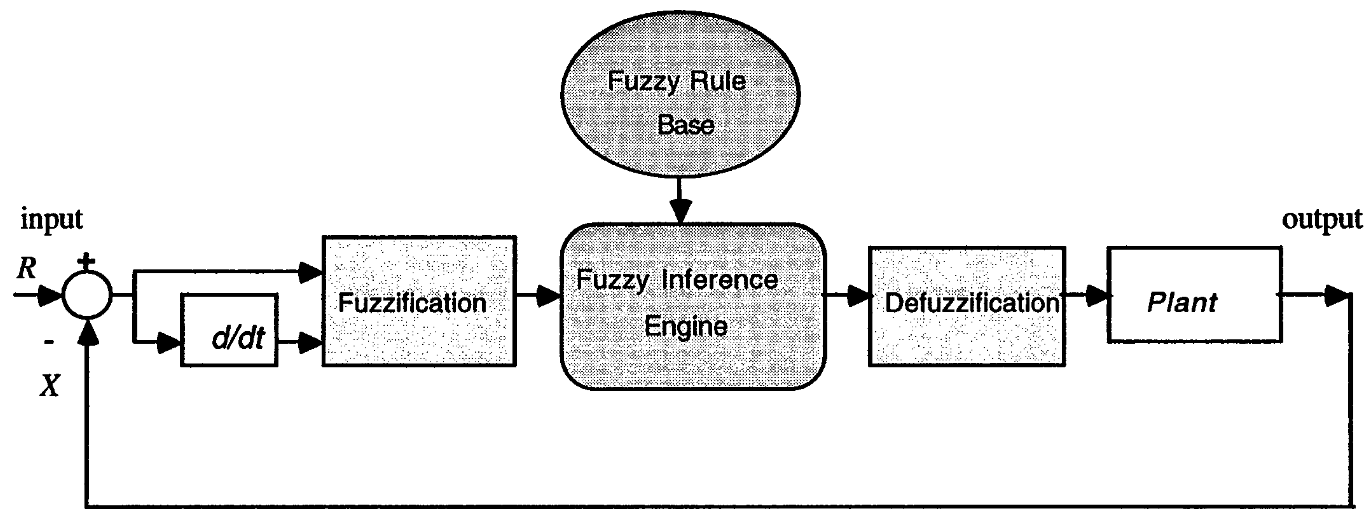


Figure 2-2: Block diagram of a fuzzy control system

2.3 Why fuzzy sliding control

Sliding mode control is a form of nonlinear control, which is robust and global stable. A sliding controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecisions. This control design is conducted in the hyperplane of the chosen variable space. In application, a boundary layer enclosing the switching hyperplane is needed to eliminate the chattering phenomenon [Slotine, 1991]. In this thesis, the concept of sliding control is extended to fuzzy set theory for the purpose of achieving a new control which can have good robustness and also is able to deal with unmodeled human expertise.

Kung [1994], Ghalia [1995] and Palm [1992] presented the idea of using fuzzy logic to solve the chattering problem for sliding mode control and further developed the fuzzified sliding mode control, in which the switch condition has been fuzzified. To develop stable fuzzy control, other approaches have been proposed based on Lyapnov stability theory [Langari, 1990, Tanaka, 1992]. By observing that both the fuzzy controller and sliding mode control can be visualized and designed in the phase plane, Hu [1994, 1995] developed another design approach, which is based on the rule base of the human expert. Using the fuzzified sliding mode control law the control rules can be tuned in the phase plane. In this thesis, the proposed design methodology explicates fuzzy partition, rule tuning, and dynamic adjusting of fuzzy partitions. Making use of the inherent advantages of sliding mode control, fuzzy sliding control can have robustness over model uncertainties and also have the capability of rejecting disturbances.

Considering the uncertainties from the task environment and the human operator, fuzzy sliding control has been shown to overcome these difficulties because it can supply the robots with varying stiffness control when the slave robot contacts the task environment. A special control structure associated with FSC was also designed to deal with a time delay. In the following sections, the FSC design methodology and the control scheme for a telerobotic system are described in detail.

2.4 Theory of Fuzzy Sliding Control

In studies of fuzzy sliding control, there are two different approaches. One approach is to directly fuzzify the switching variable S (a fuzzified sliding mode control). According to the extension principle of fuzzy sets [Zadeh, 1965], any conventional continuous controller can be extended into a fuzzified controller through fuzzifying appropriate variables. Fuzzified

sliding mode control can attenuate the chattering by introducing the fuzzy variable of S [Ghalia, 1995], which can be applied to a high order system. In the second approach, the fuzzy sliding control law is derived and used to re-design or tune the fuzzy logic rule base so as to achieve a stable, robust fuzzy controller. In this paper, we focus on the second FSC approach.

Let's consider a 2nd order system and develop the corresponding fuzzy sliding mode control law in the phase plane.

$$\ddot{x}(t) = f(x,t) + u(t) + d(t) \tag{2.1}$$

where $x(t)$ is the state variable, $u(t)$ is a control variable, $d(t)$ is a disturbance. Assume $x_d(t)$ is the desired state, and the tracking error is

$$e = x(t) - x_d(t) \tag{2.2}$$

The sliding surface (or switch line) is: $s(x,t) = 0$

where $$s(x,t) = \dot{e} + \lambda \cdot e \qquad \lambda > 0 \tag{2.3}$$

By choosing the Lyapunov function,

$$V(t) = \frac{1}{2} s(x,t)^2 \tag{2.4}$$

the reaching condition of sliding mode control can be written in the form of

$$\dot{V} = s \cdot \dot{s} = s(\lambda\dot{e} + \ddot{e}) \leq -\eta|s| < 0. \qquad \eta > 0 \tag{2.5}$$

Then from the reaching condition and the above equations, we can derive the sliding mode control law as follows.

The 1st form of the sliding control law is:

$$u = -K \cdot sgn(s) \tag{2.6}$$

where $$K \geq \eta + [f(x,t) + d + \lambda\dot{e} - \ddot{x}_d]sgn(s) \tag{2.7}$$

It is assumed that the upper bounds exist, $|\lambda\dot{e}| \leq E$, $|f(x,t)| \leq F$, $|d(t)| \leq D$, $|\ddot{x}_d(t)| \leq v$.

K can be selected as $K = \eta + F + D + E + v$,

The 2nd form of the sliding control law is: $$u = -\lambda\dot{e} - K^* \cdot sgn(s) \tag{2.8}$$

where $$K^* \geq \eta + [f(x,t) + d(t) - \ddot{x}_d]sgn(s) \tag{2.9}$$

Select K^* as $$K^* = \eta + F + D + v \tag{2.10}$$

$$sgn(x) = \begin{cases} 1 & if x > 0 \\ 0 & if x = 0 \\ -1 & if x < 0 \end{cases} \tag{2.11}$$

To attenuate the chattering in the neighborhood of the switching line, a boundary layer is introduced [Slotine, 1991]. Based on (6), we can obtain the fuzzy sliding control law:

$$u = -K_{fuzz} \cdot sgn(s) \tag{2.12}$$

where $K_{fuzz}(s)$ is a nonlinear function of |s(t)|.

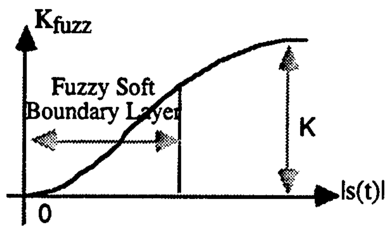


Figure 2-3: Fuzzified control value

Here |s(t)| indicates the distance from a system state $(e, \dot{e})$ to the switching line. Based on the above fuzzy sliding control law (12), the fuzzy partition of control output can be determined. The FSC law can be interpreted as the following FSC rules in the scaled phase plane.

Rule 1: IF the state $(e, \dot{e})$ is above the switching line, THEN u is negative.

Rule 2: IF the state $(e, \dot{e})$ is below the switching line, THEN u is positive.

Rule 3: IF |s(t)| is Z (Zero), THEN u is Z.

Rule 4: IF |s(t)| is S (Small), THEN u is S.

Rule 5: IF |s(t)| is M (Middle), THEN u is M.

Rule 6: IF |s(t)| is B (Big), THEN u is B.

Generally, by applying the above FSC rules and modifying the original fuzzy control rules which have been abstracted from human knowledge, a set of adjusted fuzzy control rules can be obtained. The above rules shape the scaled phase plane into soft boundary layers. Figure 2-4 illustrates the fuzzy partition and FSC soft boundary layer in the scaled phase plane. The final version of FSC rules base is organized in the form of Figure 2-5. The complete rule sets described in Figure 2-5 have been applied in the telerobot control where $e(t) = \theta_d - \theta$ (refer to Figure 3-2).

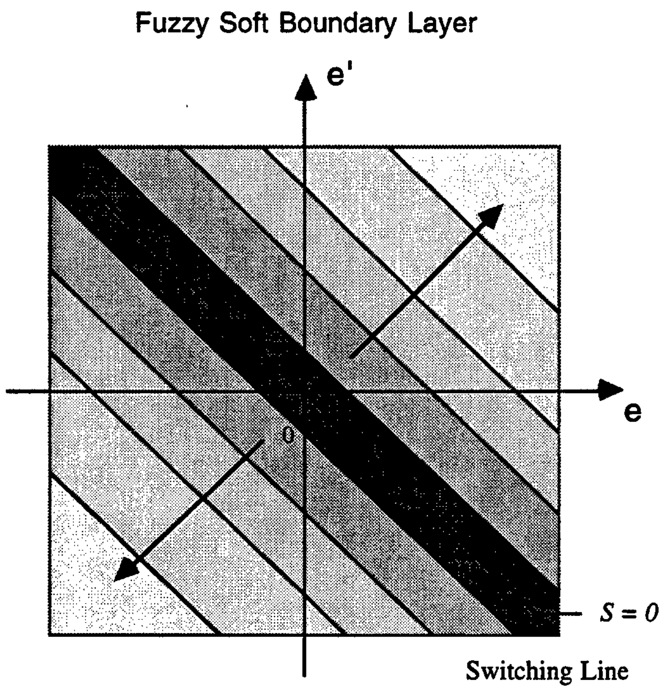
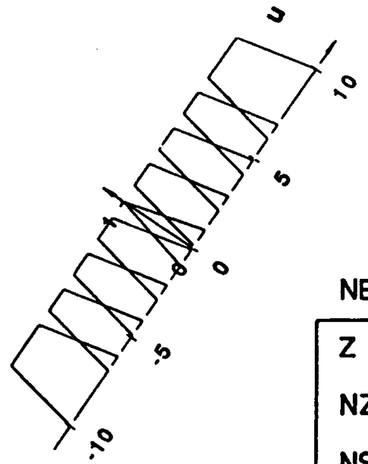
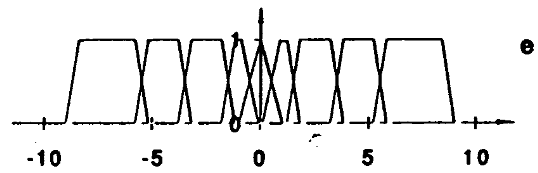


Figure 2-4: FSC in scaled phase plane





NB	NM	NS	NZ	Z	PZ	PS	PM	PB	
Z	PZ	PS	PM	PB	PB	PB	PB	PB	PB
NZ	Z	PZ	PS	PM	PM	PB	PB	PB	PM
NS	NZ	Z	PZ	PS	PM	PM	PB	PB	PS
NM	NS	Z	Z	PZ	PS	PS	PM	PM	PZ
NM	NM	NZ	NZ	Z	PZ	PZ	PM	PM	Z
NB	NM	NS	NS	NZ	Z	PZ	PS	PM	NZ
NB	NB	NM	NM	NS	NZ	Z	PZ	PS	NS
NB	NB	NB	NM	NM	NS	NZ	Z	PZ	NM
NB	NB	NB	NB	NB	NM	NS	NZ	Z	NB

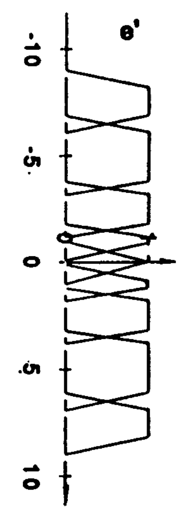


Figure 2-5: FSC rules of a telerobot

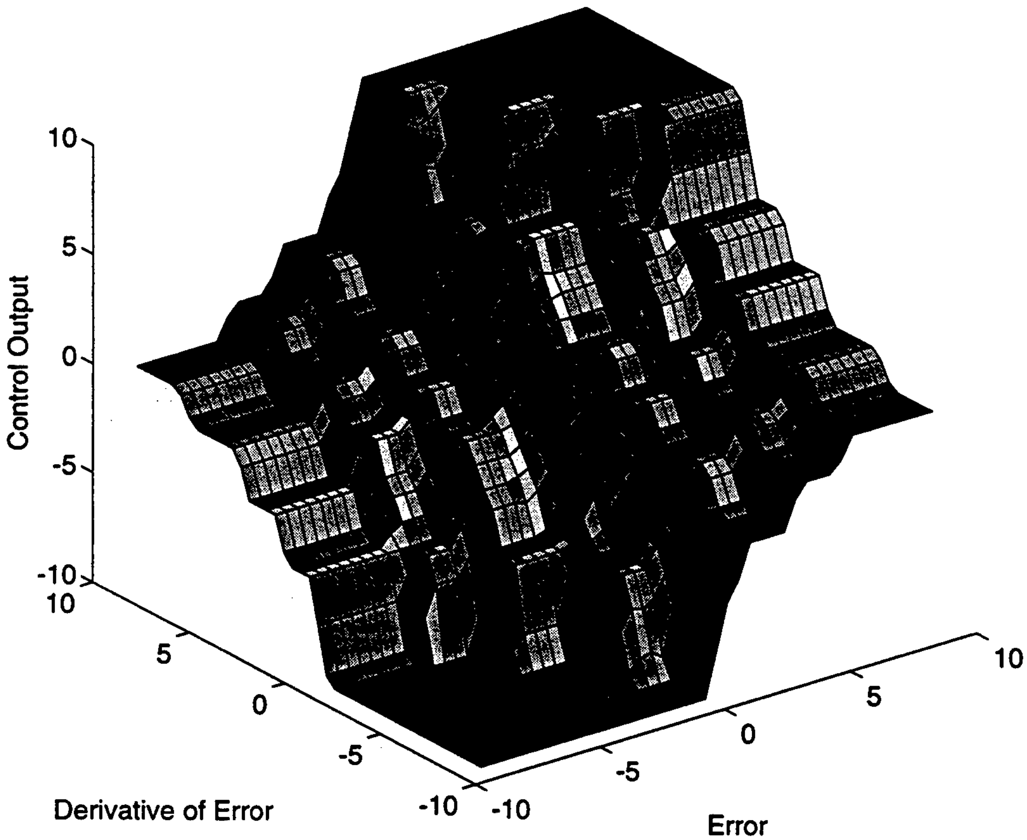


Figure 2-6: Control surface of FSC in 3-D.

2.5 Design of fuzzy sliding control

We summarize our FSC controller design procedure: 1) set up the preliminary control rules and fuzzy partitions from expert knowledge; 2) choose the switching line and the soft boundary layer; 3) tune the fuzzy partitions (membership functions) of the control variable and those for the input variables and control variable; 4) modify the control rules according to the FSC law; 5) implement the fuzzy sliding control on the general fuzzy control system structure; 6) simulate and evaluate the control system, reiterate from step 2 until satisfactory responses are obtained.

Considering the robot control applications, it is necessary to tune the scaling factors and the fuzzy membership functions, i.e. soft boundary layer tuning, which is described in next section.

Chapter 3

Fuzzy Sliding Control of Telerobotic Systems

3.1 System structure of fuzzy sliding control

Stable force reflecting control is very important for any teleoperation system with a large time delay. For some particular cases, like a telesurgery systems, precise trajectory control is also required. The passive compensation approach[Niemeyer, 1991] aims to modify the communication link into a passive transmission link, and hence smooth the force signal and dissipate the energy generated in the human operation loop. But it has been found that the passive compensation approach has a position drifting problem[Niemeyer, 1992]. In tests of teleoperation, it has been found that unstable force reflecting takes place whenever a discontinuous force signal transmitted from the slave robot is present at the master robot site and exerts on the human operator's hand, which in turn produces a force impulse and charges energy into the operation loop. In our approach, we design a FSC, that dissipates the energy locally at the master robot site as well as the slave robot site, and stabilizes the system. The following system design can achieve stable force reflecting and accurate trajectory control.

In teleoperation, three different operation modes can be identified: free motion mode, transition mode, and contact mode. The transition mode is the mode in which an operation changes from a free motion mode (without environment constraint) into a contact mode (with environment constraint) or vice versa. For different operation modes, the controller may need to change for better performance. A master-slave telerobotic system usually consists of two identical robot arms. Since the dynamics of each d.o.f. is decoupled from others, we only need to control each degree of freedom separately. Therefore we only discuss an one-d.o.f. control system in this paper.

The overall control system structure is described in Figure 3-1. In the telerobotic system, there are two robot controllers, i.e. a slave controller and a master controller. They are hybrid controllers consisting of FSC and force control (in Figure 3-2). There are two supervisors, i.e. a slave supervisor and a master supervisor, which are fuzzy inference engines for changing operation modes and for tuning controller parameters. The time delay indicates the communication (or data transmission) time delay between the master robot and the remote slave robot.

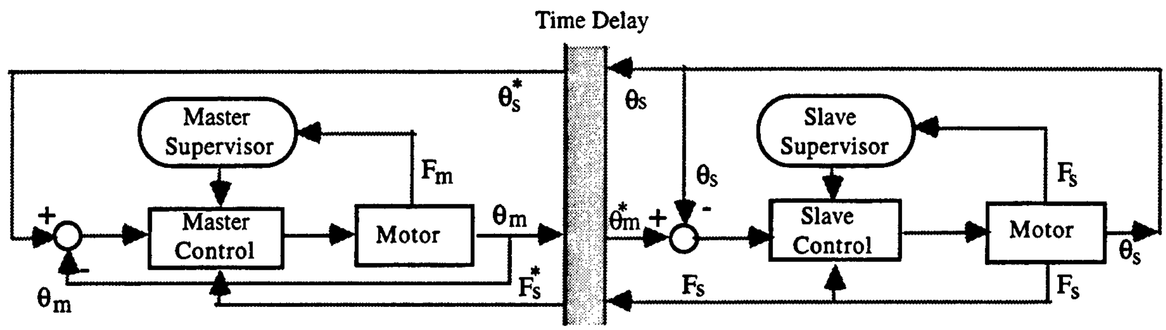


Figure 3-1: Control system structure of a telerobotic system

3.1.1 Controllers in slave robot and master robot.

The controller structures of the slave robot and master robot are the same as Figure 3-2. In Figure 3-2, θ_d is the desired position, and F_d is the desired force signal. K_p, K_d are the scaling parameters of FSC. There is an operation mode parameter a in the control system. When α=0, the controller becomes a pure force controller, and when α=1, the controller is a pure FSC position controller. If $0<\alpha<1$, the controller is a hybrid position and force controller. In addition, there is an adjustable parameter d of FSC, which is the fuzzy dead zone width. Tuning the parameters α, K_p, K_d, and d depends on the operation mode, which is governed by the two fuzzy supervisors.

For the control of the slave robot, the controller is designed as a combination of position control and force control. In the contact mode, force control will function, but in the transition mode and the free motion mode the FSC position will be dominant in controlling the robot. In the transition mode, the FSC functions as a variable stiffness controller within the soft boundary layer. The supervisor observes the operation status of the slave robot, estimates the contact situation, and switches the control modes by means of tuning the coefficient a ($0<\alpha<1$). Here the supervisor is a fuzzy inference engine. Its inputs are the computed force of the task environment and the position responses, and the outputs are the parameter α and the scaling parameters, K_p, K_d.

In the master control subsystem, F_d is the delayed force transmitted from the slave robot. And the supervisor estimates the slave operator status, tunes the parameter α, and the FSC parameters (i.e. scaling parameters K_p, K_d and fuzzy dead zone width d).

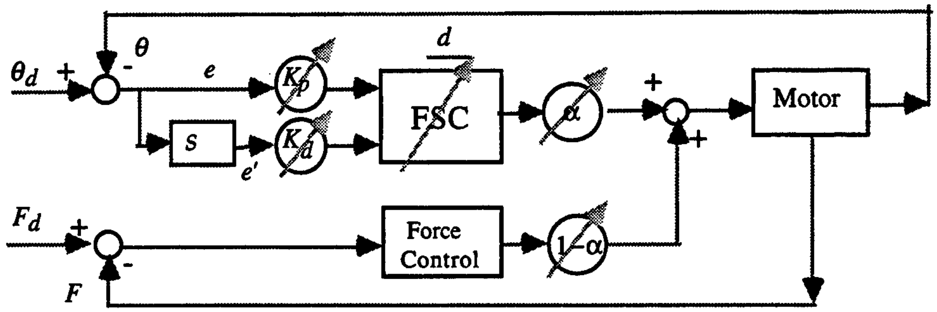


Figure 3-2: Master/Slave Controller

3.1.2 Fuzzy Supervisors

• Slave fuzzy supervisor

By observing the operation status of the slave robot, the supervisor can change controllers in different operation modes by α. Also it does the tuning of the scaling parameters K_p, K_d for the precise trajectory.

• Master fuzzy supervisor

Through estimating the operation of the slave robot, the master supervisor changes the control modes by α. In the free motion mode and contact mode, the master control is a hybrid control (FSC position control and force control). In the transition mode the master control becomes a FSC position controller, and the supervisor tunes the parameter α, the scaling parameters K_p, K_d and the dead zone width d.

• Tuning the scaling parameters

Rule 1: IF the operation is stabilized, THEN K_p, K_d increase (slave robot only).

Rule 2: IF the operation is in transition mode, THEN K_p, K_d decrease.

Rule 3: IF the operation is in free motion mode, THEN K_p, K_d are kept constant.

Among the above rules, Rule 1 is applied when the state $(e, \dot{e})$ stays within the soft boundary layer and there is no oscillation in the operation. Rule 1 changes the boundary layer's shape as shown in Figure 3-3, which gives better tracking accuracy than conventional sliding control. In transition mode, decreasing K_p, K_d means increasing the width of soft boundary layer and thus adjusts the robot stiffness relatively in a physical sense.

• Tuning the dead zone width d (master robot only)

Rule 4: IF a discontinuous force feedback appears, THEN increase the dead zone width.

Rule 5: IF the position response is disturbed, THEN increase the dead zone width.

Rule 6: IF the position response is smooth, THEN the dead zone width is zero.

In the master supervisor module, Rule 4, Rule 5 and Rule 6 are called fuzzy force filter which will shield the disturbances and the jumping force signals, and can help to stabilize the force reflecting. Figure 3-4 shows the tuning of the fuzzy dead zone.

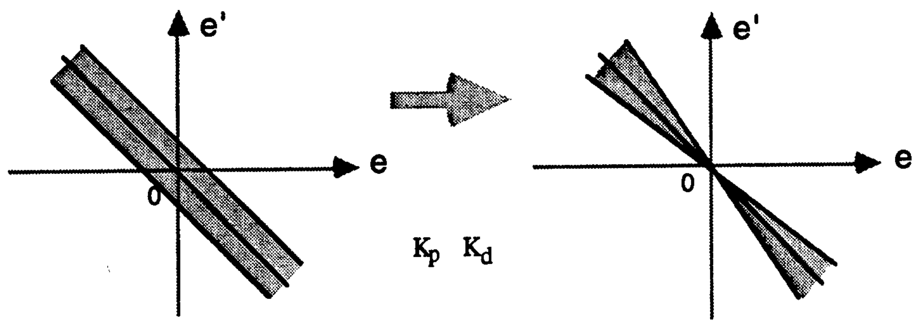


Figure 3-3: Tuning the fuzzy membership function by the scaling factors

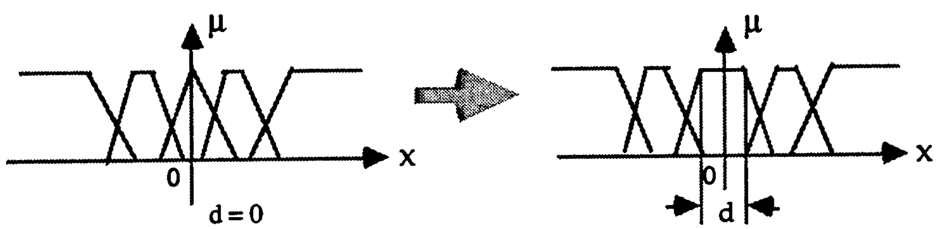


Figure 3-4 Tuning the fuzzy dead zone width

3.2 Modelling of the manipulator, human arm and environment

Precisely modeling a teleoperation system is not a easy job since the uncertainties of the task environment, human arm and the dynamics of the robot arms exist in the subsystems. A teleoperation system contains two manipulators; a master which only interacts with a human operator, and a slave which only interacts with a task. There are no direct cross interactions between the master and the task, or between the slave and the human operator. The human operator and the task both have their own dynamics. When interacting with a teleoperator system, both human operator and task have the potential to destablize the coupled system. Consequently, the interactive nature of the teleoperation system demands stability, namely so-called coupled stability when the teleoperation system is coupled with both the human and the task. In terms of stability

analysis and control design, because a human operator can change his arm dynamics, and the task dynamics vary from task to task, the controller of a teleoperator should be robust enough to handle various human and task dynamics. In this section the structure-determinant model is pursued for every subsystem of the teleoperator system.

3.2.1. Model of the manipulator

A Teleoperation system is different from a traditional manipulator. Usually a traditional manipulator directly interacts with the task environment and the dynamics of its joints are coupled. But, for a master-slave teleoperation system, the dynamics of different joints are decoupled, thus the control design can be carried out joint by joint (one d.o.f at a time). The robots that we use are Phantom robot arms. The dynamic uncertainty of each joint can be ignored because of its low inertia structure. Therefore, the master-slave manipulator system can be modeled as a one d.o.f. motor driven subsystem. Figure 3-5 shows the block diagram of the one d.o.f. control system.

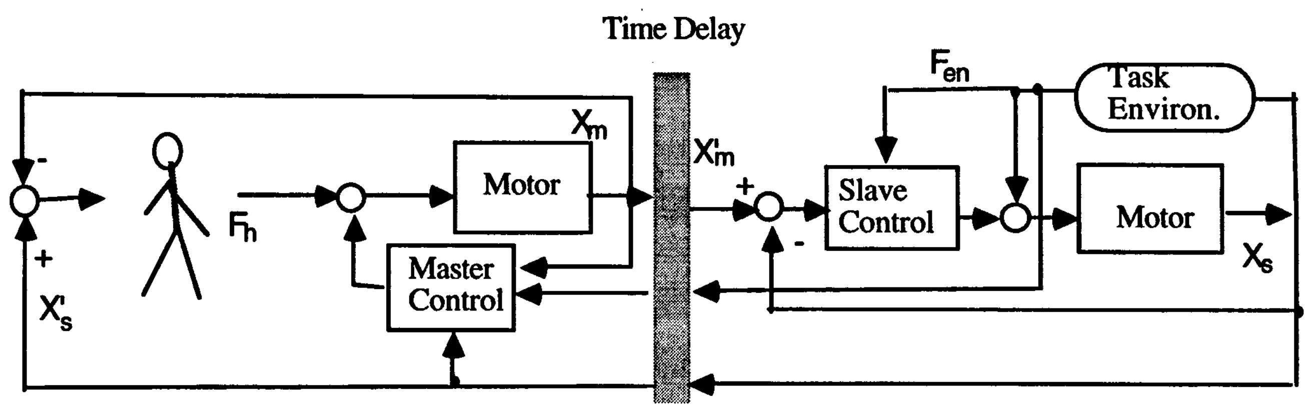


Figure 3-5: Block diagram of a telerobotic control system with one d.o.f.

3.2.2. Model of human arm

Since the human operator is inherently part of a teleoperation system, the system's dynamics can not be completely described without taking the operator's arm into consideration. However, due to the complicated dynamics of the human arm, an accurate model of arm impedance is not yet available in the literature. For most analyses of teleoperation, a human operator model has not been included. Particularly, in passive control approaches, people always assume that the operator arm can be treated as a passive impedance model. In fact, this is not true. One should consider the effect of arm locomotion during teleoperation. Because of arm locomotion, an operator can generate a force and position impulses in reacting to a step force signal and the operator can become fatigued. Hannaford and Anderson [1988] applied a linearized version of a sixth order non-linear model of one axis human movement in modeling their teleoperation system. The operator was shown to have a significant effect on the dynamics of the system. Another example can be found in the work done by Lee and Lee [1992]. They derived a third order model of the operator from considerations of the intentional mechanisms in the brain, the neuromuscular response and the human operator's arm dynamics. It has been shown by Lee and Lee that a system, without human dynamics and stable under time delay, can become unstable when a simplified model of the operator dynamics is included.

Chin [1991] summarized several different models from a systematic and physiology point of view, in which the linear lumped parameter muscle model and arm locomotion are specified. Figure 3-6 is a second order model of a human arm.

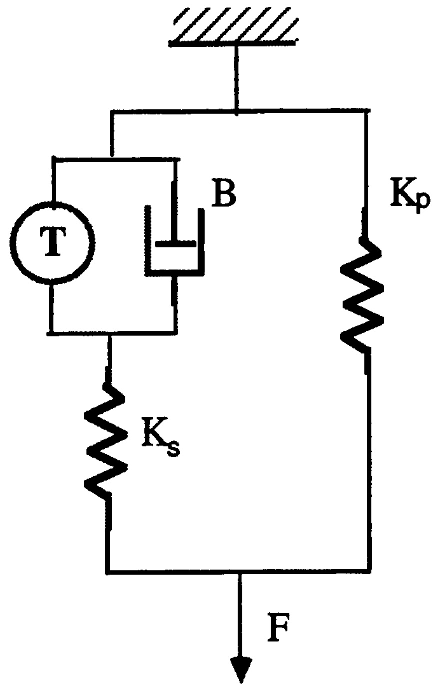


Figure 3-6: A model for a human arm (a lumped-parameter muscle model). B is a damping parameter, K is a elastic parameter for the human arm. T is the arm power source, i.e. arm locomotion.

3.2.3 Model of task environment

The concepts of impedance and admittance are useful in considering the interaction of the slave with the remote task and the interaction of the human operator with the master. Impedances accept flow (e.g. velocity) and produce effort (e.g. force) whereas admittances accept effort and produce a flow. As Hogan [1985] observes, whenever a dynamic interaction between two physical systems is analyzed the representations must complement each other. Thus, if the environment is represented as an impedance, it accepts a velocity command and produces a force as an output. Based on this consideration, Niemeyer and Slotine [1991] proposed to use impedance matching terminals in their passive control model.

In the research of telesurgery, our task environment is the patient body, particularly the abdomen of the patient in laparoscopic surgery. To simplify the physical environment a simple task model simulating the telemanipulator interaction with the tissue of the patient's body was provided by a mechanical beam. Normal force applied is nonlinear with both tangential position but linear with the normal displacement, much as would be encountered

in surgery. This provided a good test of our methods for coping with time delay. Figure 3-7 shows the task model.

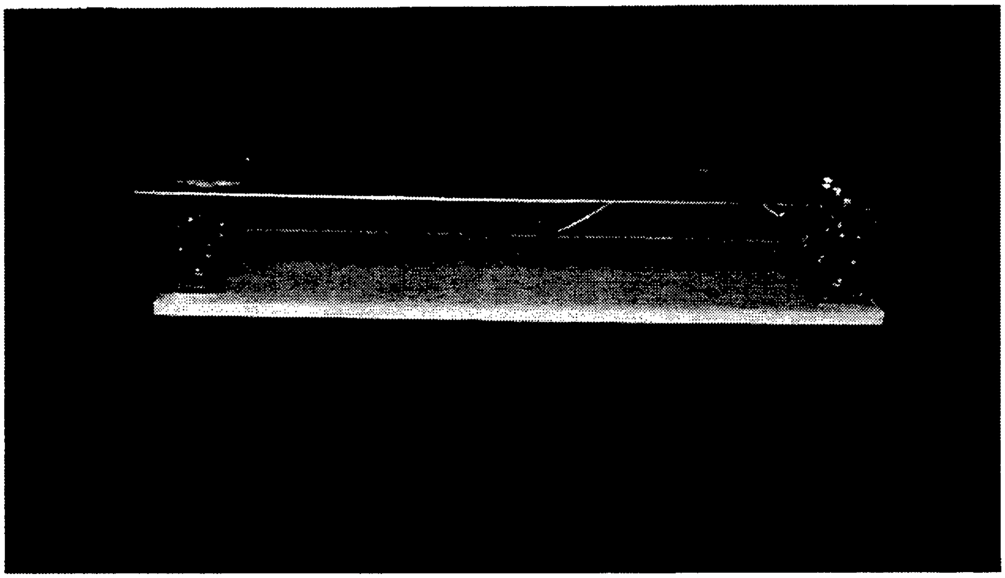


Figure 3-7: A task model simplified for telesurgery

3.3 Stability of the force reflecting and the trajectory accuracy

To prove the overall system stability of a teleoperation system with FSC, which includes human operator in the loop, one should consider the human arm dynamic model as well as human mental control model. The following is the structure of a teleoperation system proposed in the thesis (Figure 3-8).

In this system, the models of different system components are explained as follows:

e^{-sT}: telecommunication time delay (T seconds);

$G_s(s)$: slave robot model (2nd order);

$G_{sc}(s)$: model of slave controller;

$G_{ev}(s)$: task environment model at the slave site;

$G_m(s)$: master robot model (2nd order)

$G_{hm}(s)$: model of a human arm;

$G_{hc}(s)$: model of human mental control, which can be treated as a PD controller combined with a time delay about 0.1 sec.[Lee and Lee, 1992].

The model of fuzzy filter (a part of FSC in the telerobotic system) can be treated as a low pass filter in case of a step signal input in a mathematic sense, but functionally it is the logic combination of a class of low pass filters.

The stability proof can be accomplished by means of the corollary of the small gain theorem described in Appendix A. Let's start from the most inner loop, loop-1. In loop-1, since the FSC is applied, the subsystem in this loop behaves as a 1st order passive system as long as the system states reaches the switching surface (or switching line). Hence the transfer function of loop-1 is strictly small gain. In loop-2, the subsystem can be simplified into the form of Figure A-1. By applying the corollary in appendix A, we know that the loop-2 is stable and the transfer function in loop-2 is small gain too. Similarly, in loop-3, we can also prove the stability by the corollary of the small gain theorem. Therefore, the overall system is stable. The more detailed mathematic proof will be found in the future publications.

The philosophy of the stable force reflecting control in this system structure is to dissipate the energy in the master robot control loop, which is different from the passive compensation approach [Anderson and Spong, 1989]. For the master robot, we can model the human arm as a passive impedance structure plus a particular power source (impulse effort source). The goal of the FSC design is to choose the appropriate soft boundary layer and the nonlinear control output u within the soft boundary layer, and also to select the dead zone parameter d appropriately such that the local control loops at the master site and the slave site can satisfy the Small Gain Theorem respectively. If the small gain theorem can be satisfied in both local control loops (master/slave control loop), the local stability is guaranteed and thus the stability of the telerobotic system is achieved.

The trajectory accuracy of the slave robot can be obtained by means of the FSC in the slave controller. The soft boundary layer in the FSC can stabilize the tracking in the transition mode, and by tuning of the scaling parameters K_p, K_d the trajectory accuracy can be improved (refer to Figure 3-3).

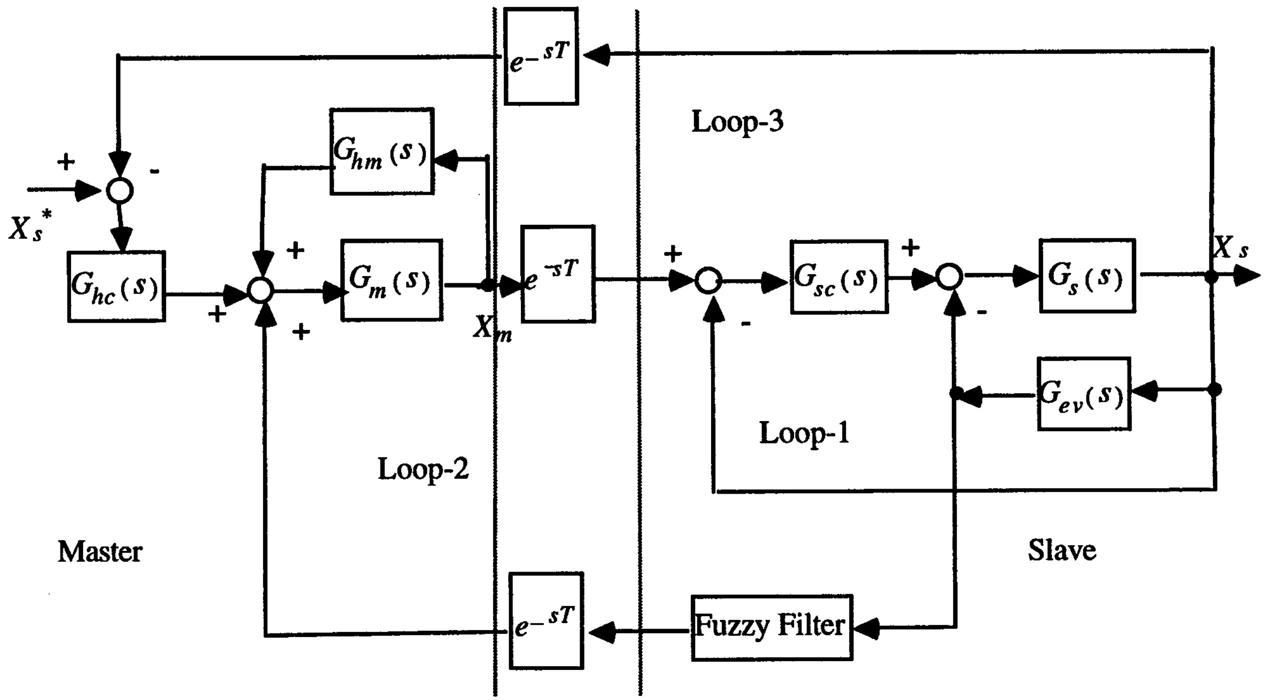


Figure 3-8: A complete system diagram of teleoperation

Chapter 4

Other Control Approaches

4.1 Raju's General Passive Control

Raju [1986,1989] first modeled a master-slave manipulator system into a two-port network and applied the two-port electric network theory to explore the stable force reflection control for the teleoperation system. Figure 4-1 shows Raju's two-port network model for master-slave teleoperation system.

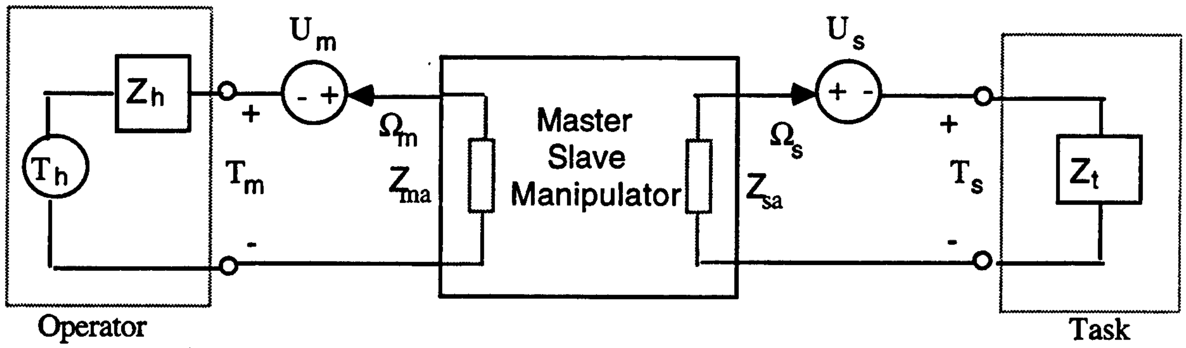


Figure 4-1: Raju's two-port network model

Z represents compliance-viscosity-inertance (impedance), T represents joint torque, and Ω represents joint velocity (for master m or slave s), all in frequency domain. Z_h and Z_t are the given impedance characteristics of the human neuromuscular system and of the task, respectively, and Z_m and Z_s are port equivalent impedances looking into the master side and into the slave side respectively of the master-slave manipulator. From circuit theory, we define the following,

$$\begin{bmatrix} T_m \\ T_s \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} \Omega_m \\ \Omega_s \end{bmatrix} \tag{4.1}$$

Therefore,

$$Z_m = T_m/\Omega_m = Z_{11} - \left[Z_{12}Z_{21}/(Z_{22} + Z_t\right] \tag{4.2}$$

$$Z_s = T_s/\Omega_s = Z_{22} - \left[Z_{12}Z_{21}/(Z_{11} + Z_h\right] \tag{4.3}$$

Let the control law for master and slave as,

$$U_m(s) = -(\frac{K_{11}}{s} + K_{12})\Omega_m(s) + (\frac{K_{13}}{s} + K_{14})\Omega_s(s) \quad (4.4)$$

$$U_s(s) = -(\frac{K_{21}}{s} + K_{22})\Omega_m(s) + (\frac{K_{23}}{s} + K_{24})\Omega_s(s) \quad (4.5)$$

Then by superposition (assuming linearity here)

$$T_m = Z_{ma}\Omega_m - U_m \quad (4.6)$$

$$T_s = Z_{sa}\Omega_s - U_s \quad (4.7)$$

where Z_{ma} and Z_{sa} are equivalent impedances looking into master and slave arms without the influence of feedback control on the respective actuators. Then from the above equations we can obtain Z_{11}, Z_{12}, Z_{21}, Z_{22}, . Raju showed that by choosing K_{ij} appropriately, one can ensure that the master-slave manipulator system is passive, namely Z_{ij} is strictly positive, thus stable for any passive termination Z_h at the master port and any passive termination Z_t at the slave port. From all his experiments Raju concluded that adjustable impedance is desirable when a master-slave manipulator is to be used in tasks made up of subtasks with different characteristics.

This approach is a general framework for passive control, and a lot of research has been based on it afterwards. However there is no guideline to tell people how to choose the control parameters such that the optimal passive control can be achieved. Chin [1991] further explored the two-port network approach and derived an optimal passive control design framework. He obtained the necessary and sufficient conditions for stable passive control.

4.2 Scattering Theory and Conservative Passive Control

4.2.1 Scattering Theory

Inspired by Raju's two-port network model, Anderson and Spong [1989], presented a method based on merging velocity and force signals, called scattering theory, which relies on the passivity of the master and the slave systems connected to each side of the communication channel. Niemeyer and Slotine developed a similar algorithm, but included terminators at both ends of the communication line. Using the analogy between electrical and mechanical systems, the teleoperator system can be modeled as a network of two-port elements representing the master, communication link and the slave subsystems. At both

ends, two one-port elements complete the bilateral control scheme: the operator and the environment, see Figure 4-2. In general, the human operator commands a position (or a velocity) to the master subsystem and receives back information about the interaction forces exerted on the slave by the environment.

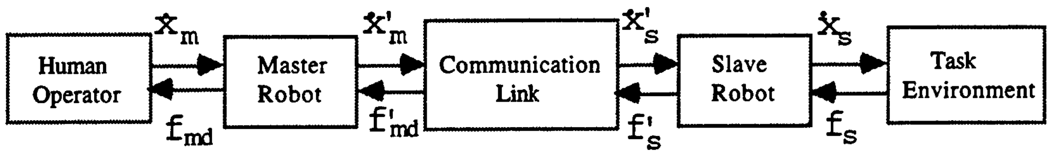


Figure 4-2: A 2-port network transmission line model for a telerobotic system

A hybrid matrix (or scattering operator) representation has been widely used to describe the performance of a teleoperation system. The description of the teleoperator is based on the relationship between effort and flow in each two-port [Raju,1986].
The hybrid matrix (or scattering operator) can be defined as,

$$\begin{bmatrix} f_m(s) \\ -\dot{x}_s(s) \end{bmatrix} = H(s)\begin{bmatrix} \dot{x}_m(s) \\ f_s(s) \end{bmatrix} \tag{4.8}$$

The Scattering Theorem states that a two port network is passive if and only if the norm of its scattering operator S is less than 1, where S can be defined for a two-port network by the relationship between the effort (force) and flow (velocity).

$$F - v = S(F + v) \tag{4.9}$$

where $F = \begin{bmatrix} f_m(s) & f_s(s) \end{bmatrix}$, $v = \begin{bmatrix} \dot{x}_m(s) & \dot{x}_s(s) \end{bmatrix}$

$$S = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\left(H(s) - I\right)\left(H(s) + I\right)^{-1} \tag{4.10}$$

The scattering theory shows that the destabilizing effects present in the tele-operator based on standard communication are caused by the non-passivity of the communications network. To obtain a passive system in the presence of any time delay, a lossless transmission line connection has to be considered. From an energy point of view, this passive element does not increase the energy of the overall system. In fact the passivity condition states that in a passive n-port, power can be dissipated or stored. The definition of hybrid and scattering matrices and the passivity conditions on their norms give tools to prove the passivity of elements in the teleoperator. By means of energy considerations and

definition of the scattering matrix, lossless transmission lines are shown to be passive (even if not strictly passive) for any time-delay of the communication network. In this case the overall system is obtained as a connection of only passive elements and therefore it is shown to be passive.

4.2.2 The equivalence between Anderson's approach and Niemeyer's approach

(1) Anderson and Spong Scheme[1989]

In this scheme, the communication network is obtained by emulation a passive lossless transmission line and adding two equivalent transformers at both ends (B and 1/B) to overcome problems with the scaling between force and position/ velocity domains. The resulting system described in power variables is:

$$f_{md}(t) = f_s(t-T) + B[\dot{x}_m(t) - \dot{x}_{sd}(t-T)] \tag{4.11}$$

$$\dot{x}_{sd}(t) = \dot{x}_m(t-T) + \frac{1}{B}[f_{md}(t-T) - f_s(t)] \tag{4.12}$$

Using the simple dynamics of the master and slave, a control scheme based on a local slave impedance control was proposed by Anderson [1989].

The resulting equation of the master and slave dynamics and controllers are:

$$M_m\ddot{x}_m = f_h + \tau_m \tag{4.13}$$

$$M_s\ddot{x}_s = -f_{env} + \tau_s \tag{4.14}$$

$$\tau_m = -B'_m\,\dot{x}_m - f_{md} \tag{4.15}$$

$$\tau_s = -B'_s\,\dot{x}_s - f_s - \alpha_f f_{env} \tag{4.16}$$

$$f_s = K'_s \int \Delta\dot{x}_s dt + B'_s\,\Delta\dot{x}_s \tag{4.17}$$

(2) Niemeyer and Slotine's scheme[1991]

In Niemeyer's scheme, the dynamics of the communication network using wave variables is expressed as:

$$f_{md}(t) = B\dot{x}_m(t) + \sqrt{2B}v_m(t) \tag{4.18}$$

$$\dot{x}_{sd}(t) = -\frac{1}{B}[f_s(t) - \sqrt{2B}v_s(t)] \tag{4.19}$$

where

$$u_m(t) = \sqrt{2B}\dot{x}_m(t) + v_m(t) \tag{4.20}$$

$$u_s(t) = \sqrt{\frac{2}{B}} f_s(t) - v_s(t) \tag{4.21}$$

$$v_s(t) = u_m(t - T) \tag{4.22}$$

$$v_m(t) = u_s(t - T) \tag{4.23}$$

The modified passive teleoperation communications network is shown in Figure 4-3, which is obviously equivalent to the system described by (4.11, 4.12)

While using the transmission line as a carrier of the signals in the tele-operator, care must be taken in the adaptation of both terminals where the impedance of the line changes and reflections occur. To avoid the reflections at the extremities of the line, Niemeyer proposed the use of terminator elements. The impedance of the terminators must match the characteristic impedance of the transmission line. Figure 4-4 represents the passive teleoperation communication network modified with terminators written in the wave variables domain.

The terminator equations are described by

$$\dot{x}'_m(t) = \dot{x}_m(t) - \frac{1}{B} f_{md}(t) \tag{4.24}$$

$$f'_s(t) = f_s(t) + B\dot{x}_{sd}(t) \tag{4.25}$$

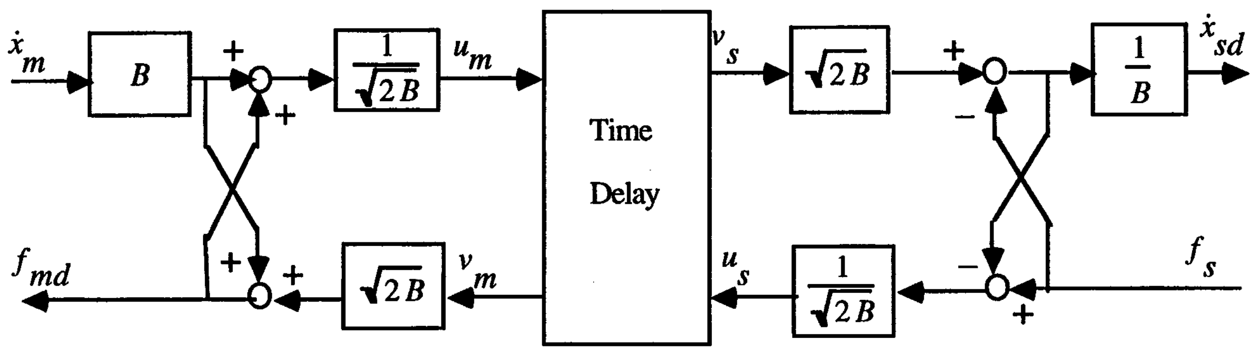


Figure 4-3: The passive teleoperation communication network model

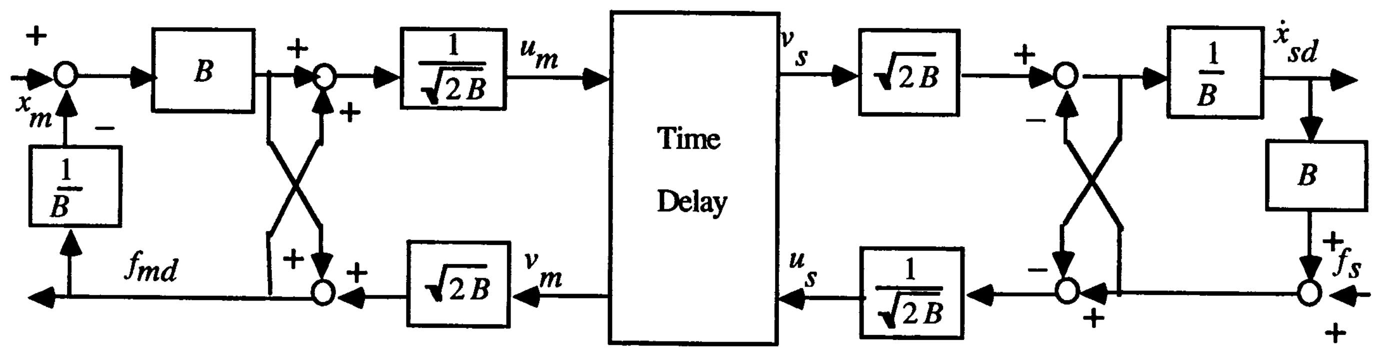


Figure 4-4: The passive teleoperation communication network with passive terminators

4.3 The remained problem with the passive control approaches

(1) Passive control with terminator (Niemeyer's scheme)

From (4.11, 4.12) and (4.24, 4.25) it is possible to derive the following:

$$u_m(t) = \sqrt{\frac{B}{2}}\dot{x}_m(t) \tag{4.26}$$

$$u_s(t) = \frac{1}{\sqrt{2B}} f_s(t) \tag{4.27}$$

$$f_{md}(z) = \frac{B}{2}\dot{x}_m(z) + \frac{1}{2}z^{-1}f_s(z) \tag{4.28}$$

$$\dot{x}_{sd}(z) = \frac{1}{2}z^{-1}\dot{x}_m(z) - \frac{1}{2B}f_s(z) \tag{4.29}$$

Where $z = e^{sT}$ time delay element.

From (4.28) and (4.29), we can see the loss of energy due to the presence of the terminators makes the system stable (in the Z domain). Also we can see that no reflection occurs at both ends of the network from (4.26), (4.27). But the position drift problems are present since in steady state ($z^{-1} = 1$),

$$\dot{x}_{sd} = \frac{1}{2}\dot{x}_m - \frac{1}{2B}f_s \tag{4.30}$$

Therefore a constant value of f in the velocity signal is integrated resulting in a position ramp for the desired position of the slave.

(2) Passive control without terminator (Anderson's scheme).

The scheme proposed by Anderson, (4.11) ~ (4.17), includes local controllers at the master and slave sides. Let the elements of B'_m and B'_s be equal to B. From (4.13) ~ (4.19), using the equations of the controllers, we obtain:

$$u_m(t) = \sqrt{2B}\dot{x}_m(t) + v_m(t) \tag{4.31}$$

$$u_s(t) = \frac{1}{\sqrt{2B}} f_s(t) - \sqrt{\frac{B}{2}}\dot{x}_s(t) \tag{4.32}$$

$$f_{md}(z) = 2B\dot{x}_m(z) + z^{-1}f_s(z) - Bz^{-1}\dot{x}_s(z) \tag{4.33}$$

$$f_{md}(z) = 2B\dot{x}_m(z) + z^{-1}f_s(z) - Bz^{-1}\dot{x}_s(z) \tag{4.34}$$

From equation (4), we see that the reflection does exist at the master side, but there is no reflection at the slave side, which makes the system stable. We can get the same result from

(15) in Z domain. In addition, at steady state from (15), we obtain $f_{md} = f_s$ and $\dot{x}_{sd} = \dot{x}_m$. Therefore, no position drift is produced by the coordinating force signal in this case.

4.4 Modification of passive control to compensate position drift.

As described in the previous sections, the presence of the matching terminators modifies the overall communication system in terms of power reflections causing position drift on the slave desired position signals. In fact, the term f_s in (4.29) at steady state provides constant input for the slave desired velocity and therefore an increasing position set-point for the slave controller. This effect can be neglected if the time length of the teleoperation task is not considerably large, but in practical applications the importance of the drift compensation is evident.

The proposed scheme is essentially based on a compliance controller at the slave side [Kim, 1992]. In place of the velocity signals this scheme is based on transmitting the increments of the sensor position. Each control cycle the communication network receives the increment of the master position and provides to the slave side the increment of the desired position. The control algorithm corrects for the f_s steady state value avoiding the drift problem. This command is then integrated to obtain the set-point for the slave position. The incremental desired position provided to the slave compliance controller is therefore expressed as:

$$\dot{x}'_{sd} = \frac{1}{2}\dot{x}_m \tag{4.35}$$

Figure 4-5 is the block diagram of the compensation scheme, which implies the insertion of a block $1/2B$ at the slave side. The value f_s is therefore multiplied by the factor $1/2B$ and then added to the original $\dot{x}_{sd}$ to compensate for the steady-state component of the coordinating force. The derived signal is then used as input for the compliance controller realized at the slave side.

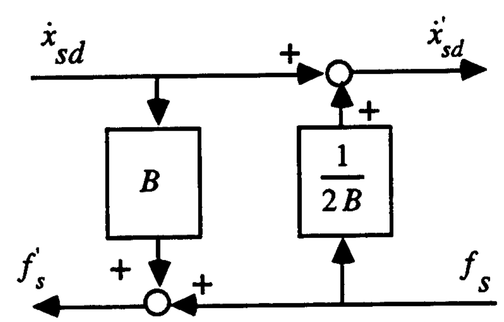


Figure 4-5: An additional link for drift compensation

4.5 Supervisory control for optimal performance

As described in the previous sections, the drawback of an ideal "transparent" force reflection is the limit of human capability in handling certain tasks. In order to improve the performance of force-reflection teleoperation, we can categorize different tasks by different requirements of the sensory information and actuation needed to accomplish the tasks. A human operator can select the corresponding control models with respect to different tasks. On the other hand, teleoperation is mostly conducted in unstructured environments that are either hazardous or too costly for human operators to reach directly. There are no mathematical models to describe the teleoperation processes under different tasks for the purpose of automatic decision making. But the human operator can take care of it. Through dynamic masking by the mechanical structure of master and slave manipulators, a human operator can still accomplish the task by functioning as a robust and adaptive controller. With a large amount of knowledge accumulated from experience, a human operator can retrieve and modify his knowledge easily in coping with new tasks. Consequently, the human operator is very adaptive when there is little prior information about the task model and/or when there is too much noisy sensory information. The robust and fast computational ability also allows him to plan motion effortlessly when the task model is available but not accurate. Therefore, an ideal teleoperation system which provides a transparent interface between the operator and the task can take full advantage of human capability.

Supervisory control can offer not only the teleoperation system with the capability of intervening at various levels to perform control along a continuum from direct manual control to quite high-level supervisory command and control, but also the capability of coping with time delay as well. The theory of supervisory control was initially developed in the Human Machine Systems Lab at MIT in the 1960s and 1970s. Sheridan [1983] discussed the concept of supervisory control extensively in 1983. The advantages of supervisory control in teleoperation are the following:

- Supervisory control encompasses a wide range of options for remote manipulation. A human supervisor is encouraged to select the most effective means to perform a certain task.
- Supervisory control can avoid the time delay problem by closing the control loop within the remote site.

Under supervisory control (Figure 4-6) the operator sends coded instructions to the remote telerobot specifying subtask conditions and procedures with reference to sensor states that must be satisfied. The operator's inputs could range from a purely manual analog

command, demonstration in time and space what is intended, to a highly abstract symbolic command made up of alphanumeric keystrokes. The instructions are sent open loop relative to the human. The remote computer then interprets the message and acts on the sensor information available to it about its own environment. The control loop for the dynamic behavior of the robot is closed within the remote site, where there is no time delay in the loop, and the control mode is selected based on the supervisor's command. The remote computer then relays that information which is deemed important and necessary for effective supervision back to the operator, the responsibility for the specific details of control being left to the subordinate computer.

Supervisory control of teleoperation has been investigated for our project (telesurgery). Some studies were done on the master-virtual slave and virtual task environment. For complex teleoperation tasks like telesurgery, there are currently difficulties in the human-machine communication interface on the supervisory side, which prevents efficient implementation of this control approach. In the near future, we believe, with better virtual reality technology, supervisory control will show its potential in advanced Teleoperation, especially in telesurgery.

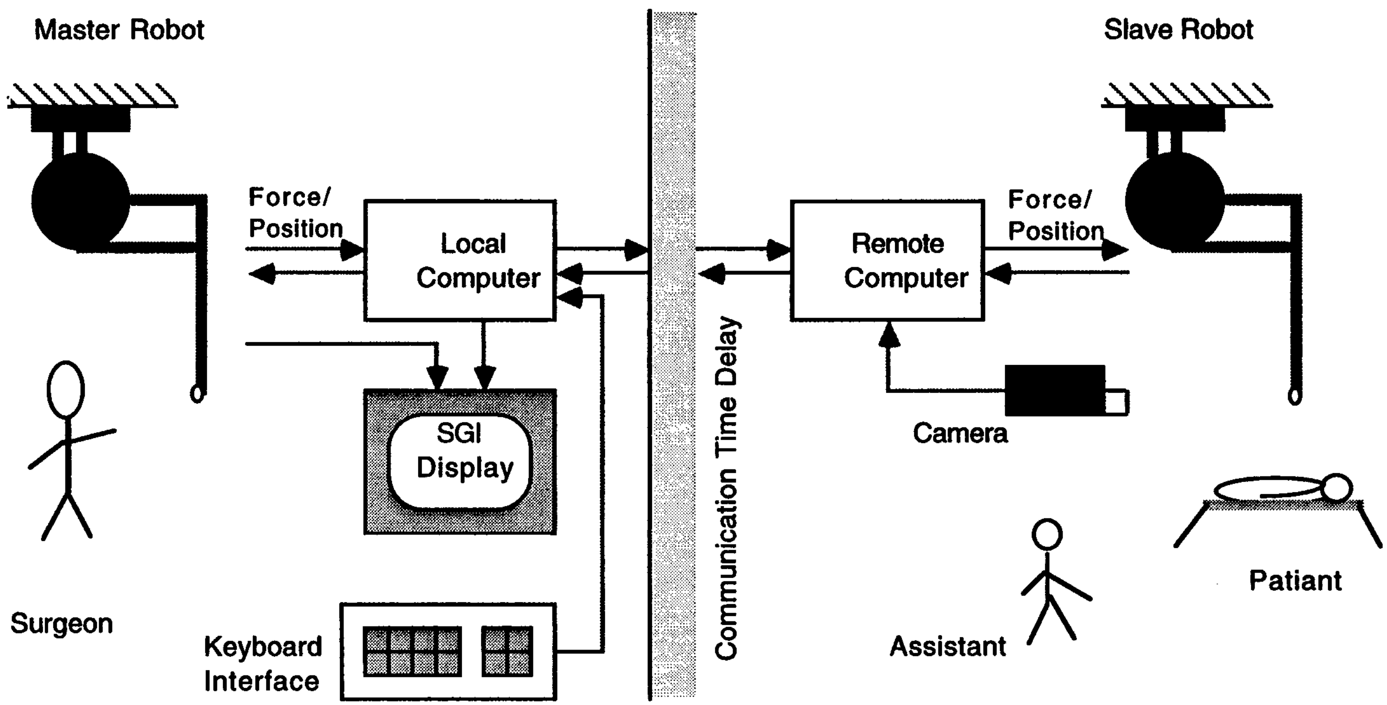


Figure 4-6: System structure of supervisory control

Chapter 5

Experimental Studies on FSC with a Virtual Environment

In the previous chapters, the design methodology of FSC and the system configuration of a telerobotic system with time delay were elaborated. It is interesting to evaluate the design of the FSC controller and to compare with some related controllers, such as sliding control with fixed boundary layer, adaptive deadzone control, and linear PD control in the first stage of the research. By taking advantage of computer graphics and dynamics simulation techniques, a virtual slave robot with a virtual environment has been developed, which gives us convenience to investigate different control approaches with respect to different time delays. This chapter addresses the actual master-virtual slave experiments.

5.1 Configuration of an actual master-virtual slave telerobotic system.

In a scientific sense, performing experiments on an actual master-virtual slave telerobotic system with virtual environment gives the following advantages in research:

(1) This system can supply the subject with sufficient interaction with the environment. The force reflection is realized by the master robot.

(2) The virtual slave robot, virtual environment and virtual communication delay box makes it possible for us to avoid the hardware difficulties and to concentrate on the theoretic research in the early stage.

(3) With the virtual environment and virtual communications delay box, one can easily conduct experiments in different settings by means of selecting different parameters.

(4) Experimenting with the virtual models reduces the safety problem.

Figure 5-1 describes the configuration of an actual master-virtual slave telerobotic system. In this system, there are the following components: a master robot (3 d.o.f.), amplifiers box, data acquisition card (computer interface with encoders, D/A converters), a master robot control module, slave robot dynamics simulation, slave control, graphics display, time delay box and virtual beam model. All the control algorithms, virtual models, and graphics are implemented by a Pentium computer. Figure 5-2 shows the structure of Phantom robot (master robot in picture).

The mathematic model of the nonlinear beam model is described in appendix C.

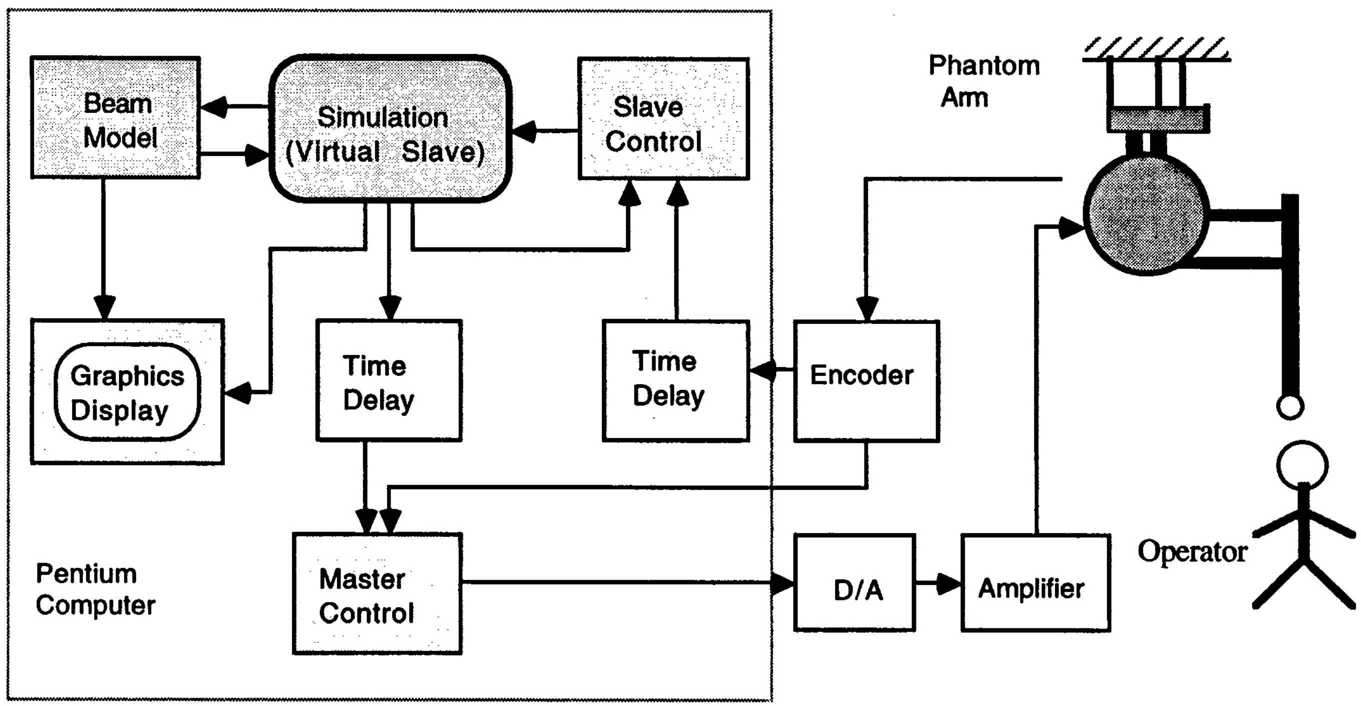


Figure 5-1: Configuration of an actual master-virtual slave telerobotic system

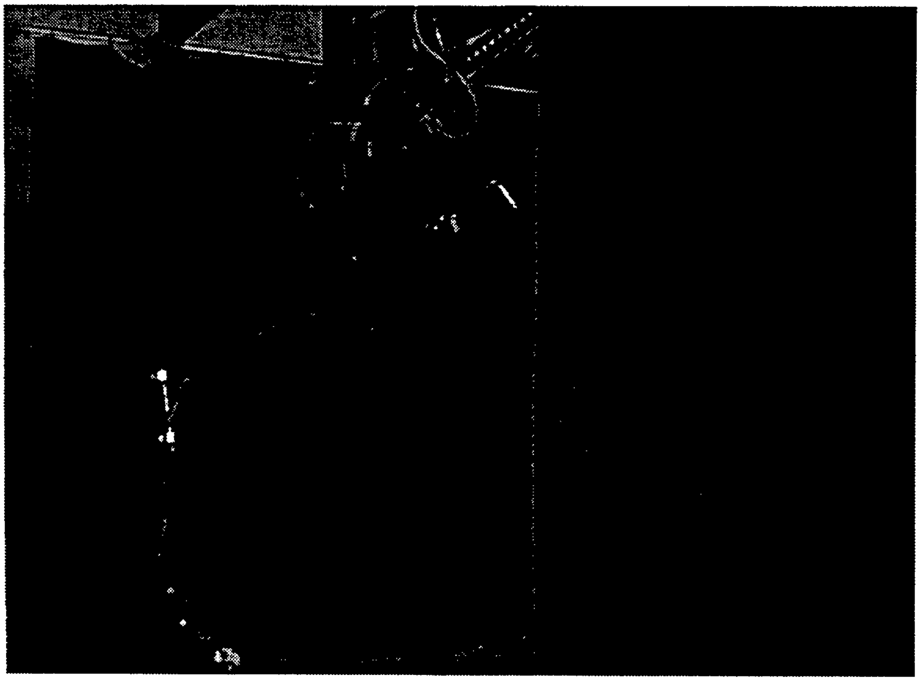


Figure 5-2: The structure of Phantom robot

5.2 Human Subject experiment design

In telerobotics, human subject experimenting is very important because the human operator is one component in the whole telerobotic system and the human interaction is not in consideration of the design of low level robot controllers. As described in previous chapters, during a teleoperation process, the human operator is in the outer loop of the teleoperation system and he/she controls the teleoperation process through visual feedback and force feedback. Improved operation can be achieved by means of a better human-machine interface, such as Supervisory Control, which is not the focus of this research.

The designed stable controllers are in the inner loop of the master-slave telerobotic system. The control design is based on the model of the robot dynamics and some assumptions for the task and human operator. Evaluation of the overall system performance becomes quite necessary for us to judge the system control design and verify the assumption we made. Therefore, human subject experimenting is a very crucial part in the design of a teleoperation system.

Using the above system (in section 5.10), human subject experiments can be easily conducted for a particular controller with respect to different time delays. The task in each case was to move the real master robot arm so that the virtual slave arm contacted the virtual beam at a given point from a free space starting position, apply a small force, then slide along the beam to another specified point while maintaining force contact.

Using the master-virtual slave system, the following control techniques were studied:

- Fuzzy sliding control;
- Sliding control with boundary layer;
- Adaptive dead zone control;
- Linear PD control;

Ten MIT graduate students were chosen randomly as subjects. Time delays of 0, 100, 500, 800, and 1000 ms were tested. During the experiment, the dynamic response data were recorded and used to do objective evaluation based on the vibration magnitude. Subjective difficulty evaluations were also made based on a subjective rating guide.

5.3 Results Analysis.

Figure 5-3 shows the statistics box plots of the subjects' experimental data in four different cases: traditional PD control; Fuzzy Sliding Control (FSC); Sliding Mode Control with Boundary Layer (SMC/BL); Adaptive Dead Zone Control (Adaptive DZC). The

information shown in the plot is the subjective "Easiness" rating, which depends on the control stability of robots, magnitude of position vibration and the fatigue tolerance of the operator's arm.

Plotted in Figure 5-4 are the typical dynamic responses of the subject teleoperation experiments (1 second time delay). The measurement of vibration magnitude of the position dynamic responses, which were recorded during every subject's experiment, gives us the objective evaluation of the controllers with respect to the time delays.

Comparisons of the four controllers are shown in Figure 5-5 and Figure 5-6. In Figure 5-5, the subjective evaluations are based on the mean value of the corresponding subjective "Easiness" rating. Similarly the objective evaluations are plotted based on the mean values of the objective measurement of the position vibrations (Figure 5-6).

The Conclusions we can draw from the comparisons are the following:

1) From the comparison plot of subjective evaluation (Figure 5-5), it is shown clearly that FSC was the best, and PD control was the worst control approach in dealing with time delay. SMC/BL and Adaptive DZC control approaches were close to the FSC approach.
2) From the comparison of objective evaluations (Figure 5-6), we observe that the best control is FSC, and PD control is the worst case. The other two approaches, Adaptive DZC, and SMC/BL are better than PD and close to the FSC approach.
3) While the time delay increases, the performance of the teleoperation degrades.
4) The critical time delay point is roughly at 100 ms according to our experiment system, which means that when time delay becomes larger than 0.1 second the system performance starts to degrade.

The reason that the evaluation of SMC/BL and Adaptive DZC are close to the best approach (FSC) in the experiments can be explained as follows: FSC is a special sliding mode control, which has a soft boundary layer and varying dead zone; The adaptive DZC or SMC/BL only has one of the characteristics, both of which are significant in improving the system performance.

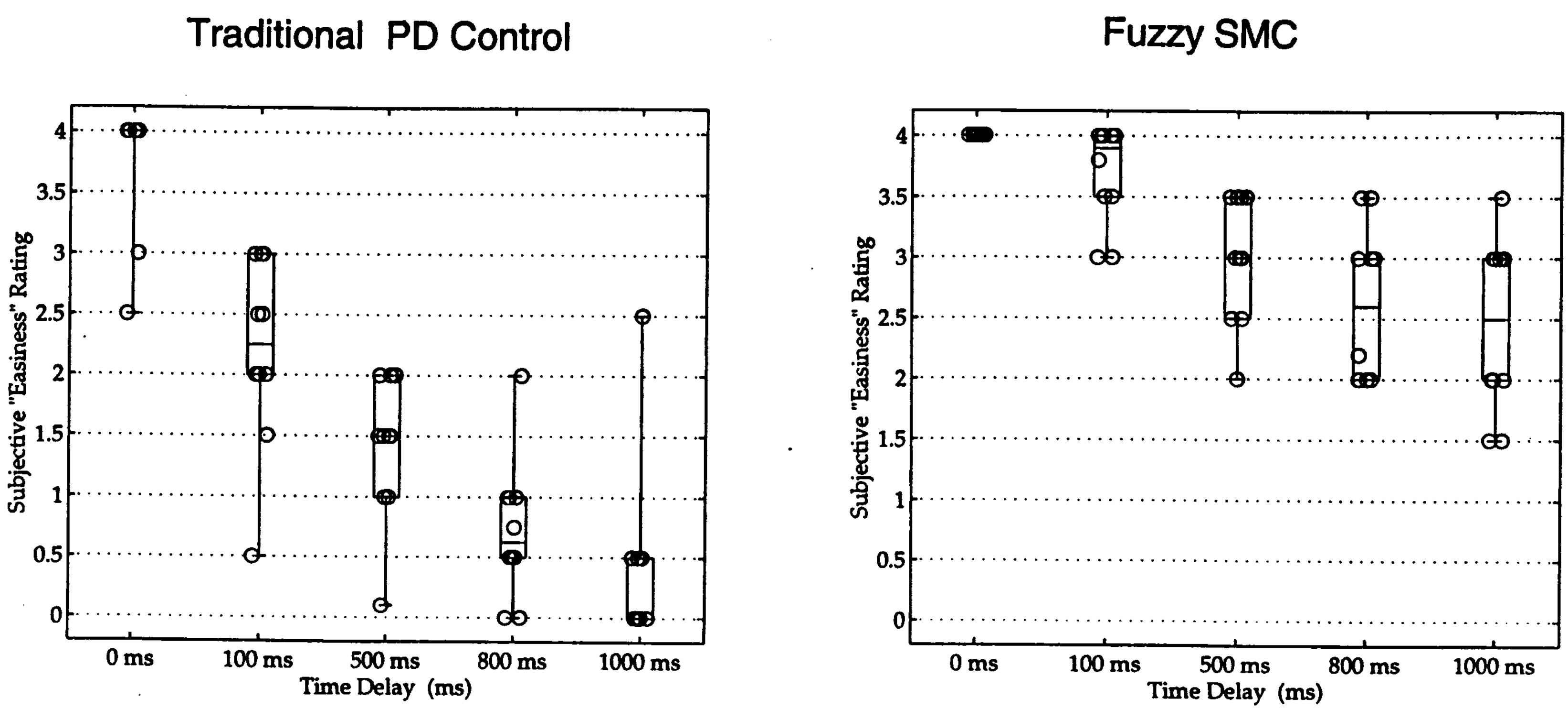


Figure 5-3: Statistics box plots of the subject experiment data. (a) PD control; (b) FSC control

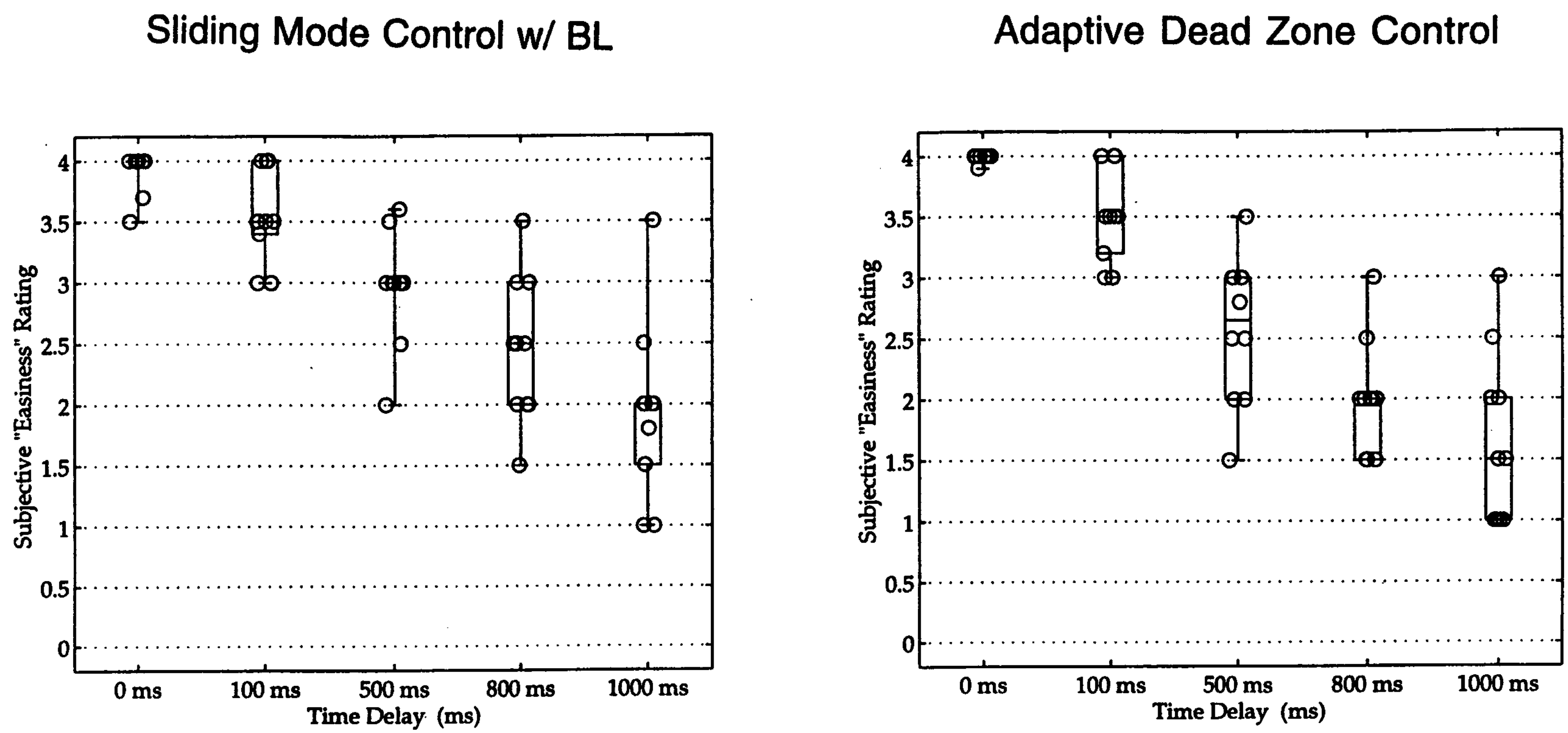
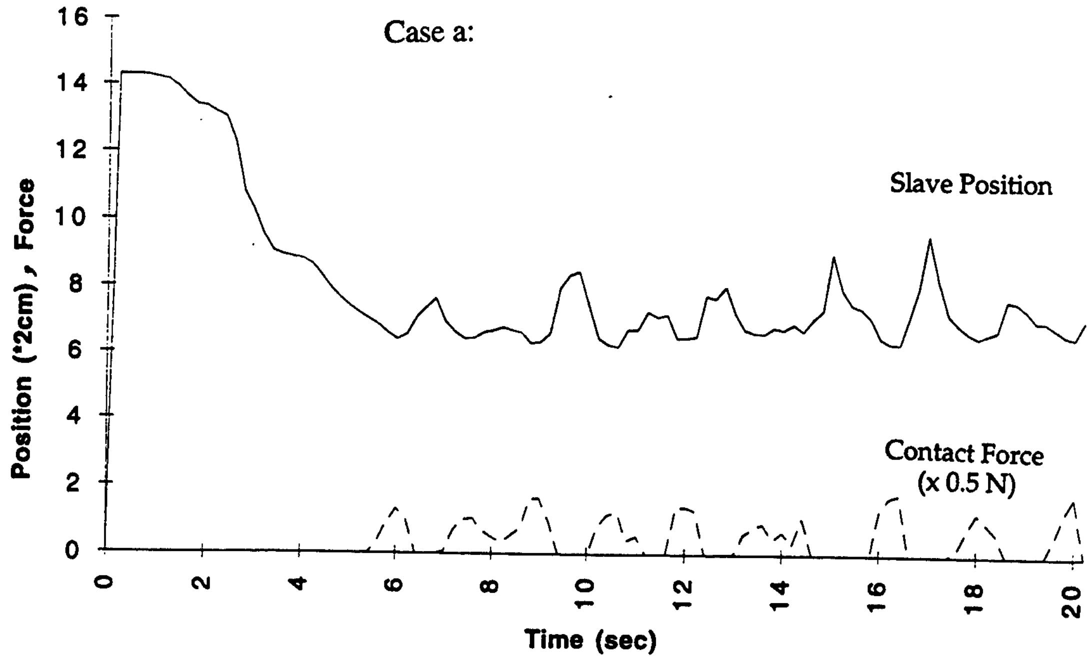


Figure 5-3: Statistics box plots of the subject experiment data. (c) Sliding control; (d) Adaptive Dead zone control.



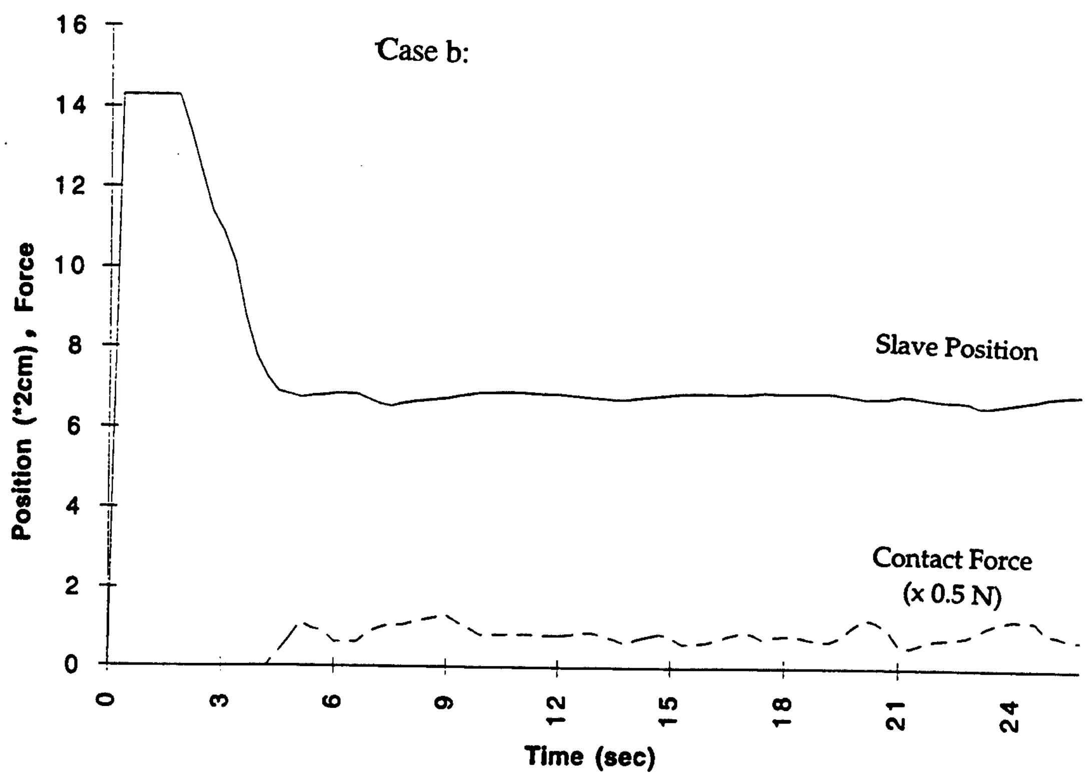


Figure 5-4: Typical dynamic responses from the subject teleoperation experiment (1 second delay). Case a: PD control; Case b: FSC control.

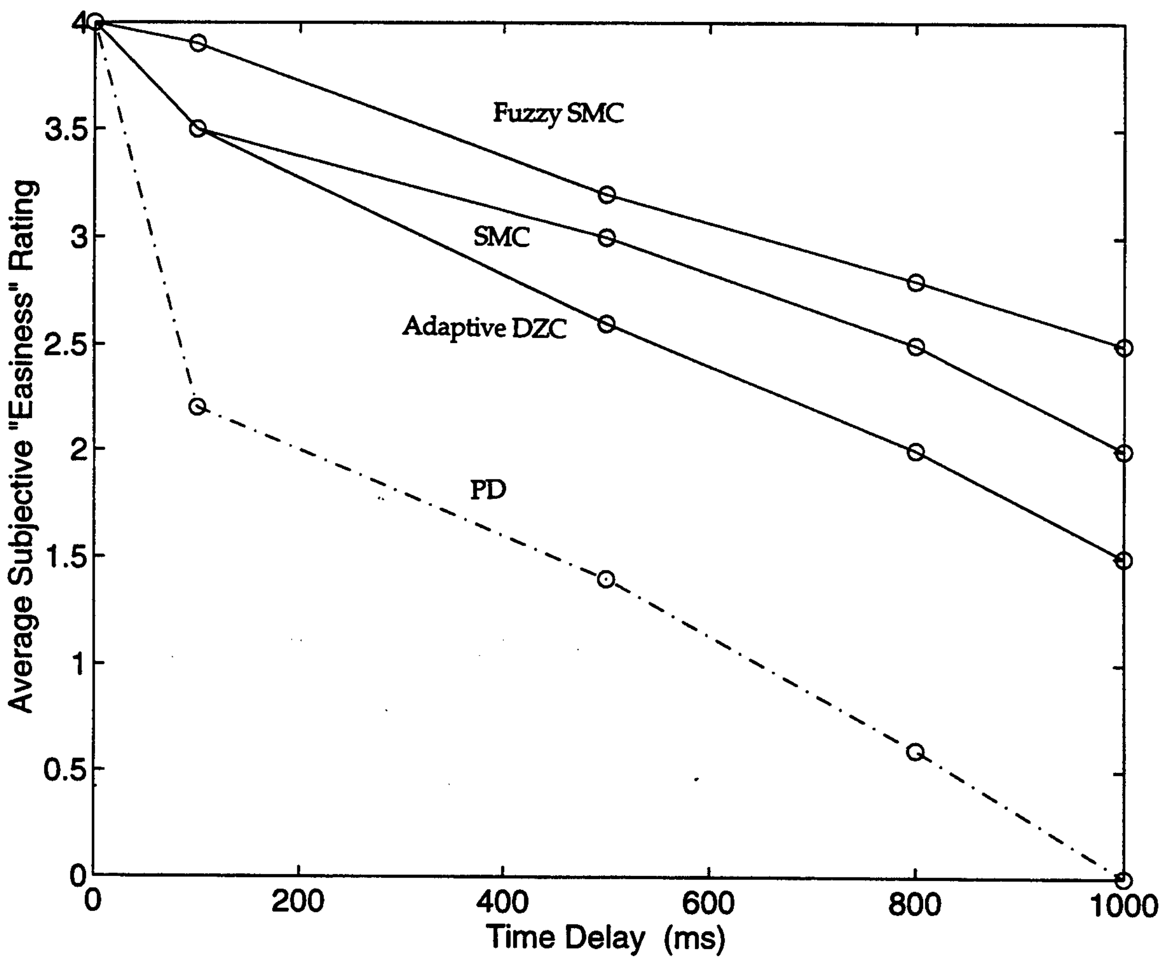


Figure 5-5: Comparison of controllers by subjective evaluations

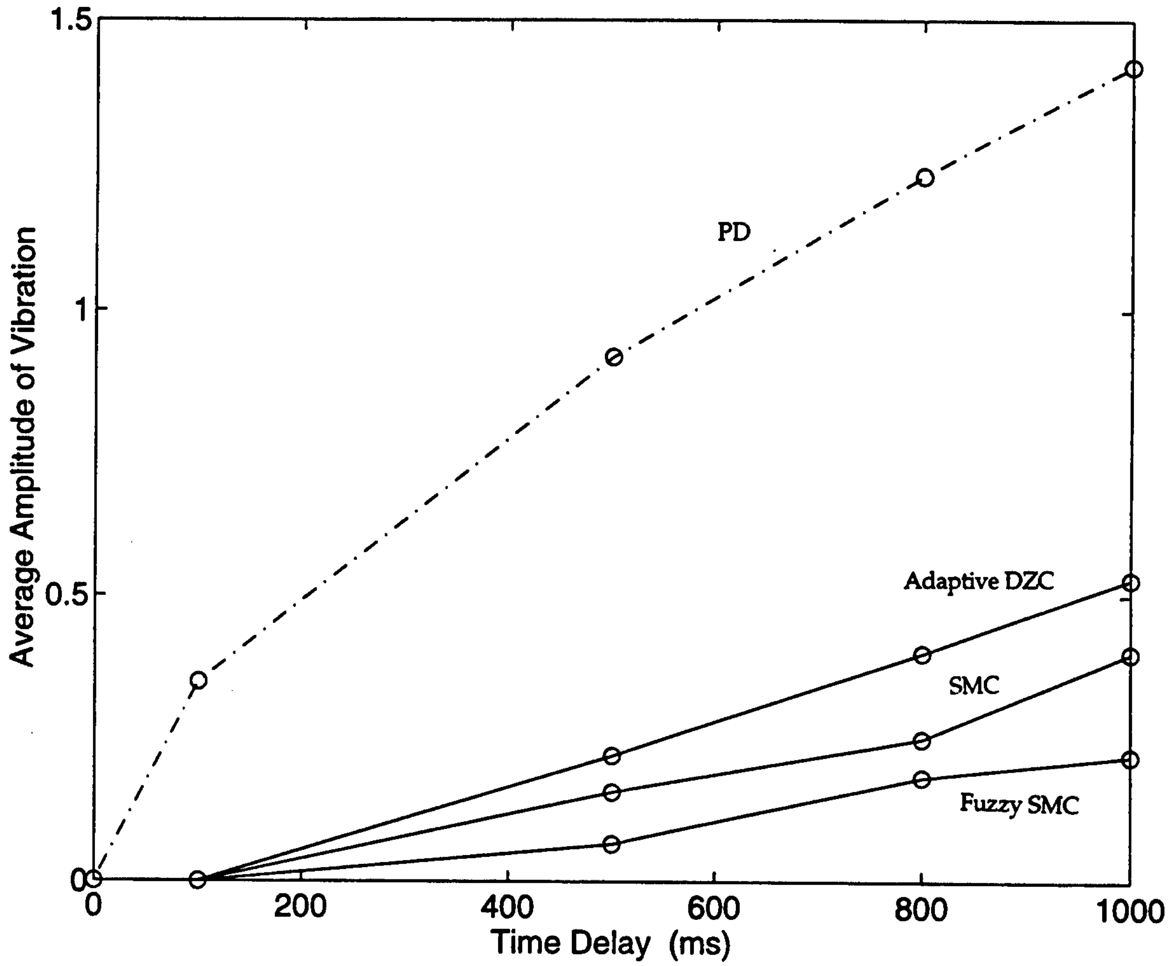


Figure 5-6: Comparison of controllers by objective evaluations

Chapter 6

Design of a Telerobotic System

6.1 System Configuration

6.1.1 System for telesurgery demonstration

Figure 6-1 shows a diagram of the telerobotic surgery system in the Human Machine Systems Lab. The major components of the system are:

• A master-slave teleoperation system, which is composed of a pair of Phantom haptic feedback arms and has stable force reflecting control (3 d.o.f.). The Phantom arms that we use are identical in kinematics and are mounted (see Figure 6-2) such that an operator standing with his or her shoulder under the robot base would have full access to the regular range of human arm motion. The phantom arms have a very low inertia structure which implies ignorable uncertainty of robot dynamic parameters and gives us an advantage in dynamic control.

• Two control computers which are used to control the master robot and the remote slave robot respectively. The corresponding data acquisition cards for robot control are installed in each machine.

• A telecommunication subsystem. A teleconference equipment set is used in the telesurgery system to support video (image), audio transmission and control data transmission as well, through three ISDN lines. For short distance communication, the minimum time delay due to image compression and decompression is about 0.6 seconds (round trip) [Zydacron, 1996]. There are two computers which function as two telecommunication terminals, one near the operator, the other close to the remote patient.

• Two data transmission links between control computer and telecommunication terminal. We have tested two different types of data links between two PCs. Ethernet was one option, but it was only marginally acceptable for force reflection. A bidirectional parallel dynamic data transmission link developed in our lab is the cheapest and fastest way to do this among serial port data transmission, ethernet transmission and other options.

• Laparoscopic surgery simulator (physical task environment) with surgical tools [Ottensmeyer, 1996].

• Mouse pointer overlay device, which is designed especially to offer a human machine interface for the surgeon. Basically, the mouse icon is superposed on the image from the patient, and thus the surgeon can send instructions visually to the remote assistant by

moving the mouse icon as a remote pointer. A SGI computer with video overlay hardware is applied for this purpose.

• Safety Devices. There are two switches, a handle switch and a foot switch to supply the surgeon and assistant with appropriate intervention, respectively. An extra electronic protection card is installed in the slave robot's amplifier box.

Fig. 6-2 shows a picture of the telesurgery system.

6.1.2 System for the force reflecting control experiment

To test and evaluate the designed controller, a particular system configuration was designed (Figure 6-2) with a beam model.

The major parts are the same as Figure 6-1, but the task environment has been changed to a physical nonlinear beam model which is supposed to simulate the patient's abdomen. In addition, a virtual delay box (computer delay buffer) was added to the experimental system for the purpose of adjusting time delays.

6.2 Hardware design

(1) Physical beam model and the force feedback sensing instrumentation (see Figure 6-3). This subsystem is used to give the subject visual force feedback such that the force at the end effector can be kept constant during experiments. It can also provide direct force information for the evaluation of controllers in test. There are eight strain gages in the force detection circuit. Four gages are used to obtain the force information at two symmetric locations on the beam, and four other gages are simply applied to compensate for the temperature effects. The additional filters and amplifiers can supply the data acquisition board (A/D) with precise signals (Figure 6-4). One PC (486) is used to process the information from the force sensor (strain gages) and displays the force response dynamically.

(2) Slave electronic protection circuit. This circuit provides us quick torque limit protection for the three joints of the slave robot.

(3) Bidirectional parallel port dynamic data transmission link. The newly developed software can offer the user a cheap way to do fast dynamic data transmission between two PCs through a regular parallel port. This software includes data security checking and control signal handshaking protocol. There is a particular connector to link the two parallel ports appropriately.

6.3 Software design

All the software has been developed in Borland C++ (in the DOS environment). The main program can supply a window interface for the user. The operator can select the particular control subroutine by mouse and the arrow keys on the keyboard, and the time delay too. Currently the software developed for the project has the following functions:

- Interface with the robot control ports, encoder ports.
- Time delay buffer module.
- Three different versions of controller subroutines for three experiment systems (e.g. actual master-virtual slave teleoperation system, master-slave teleoperation system with beam model, and master-slave telerobotic surgery system).
- Data transmission software: Bidirectional ethernet data transmission software and bidirectional parallel port data transmission software.
- System pretest software. the user can check the encoder port and reset the control port of the robots and the encoder neutral position.
- Safety on-line protection software: position protection is to check the position error between the master and the slave, and velocity protection sets a velocity limit for the robots.

Listed bellow are the controller subroutines available for three different experiment systems developed for the project:

(1) master-virtual slave Teleoperation system control software

- FSC
- Linear PD control
- Supervisory control
- Passive control
- Predictive display

(2) Master-slave Teleoperation system control software with beam model

- FSC
- PD control
- Passive control

(3) Master-slave telesurgery system control software

- FSC
- PD Control
- Passive Control

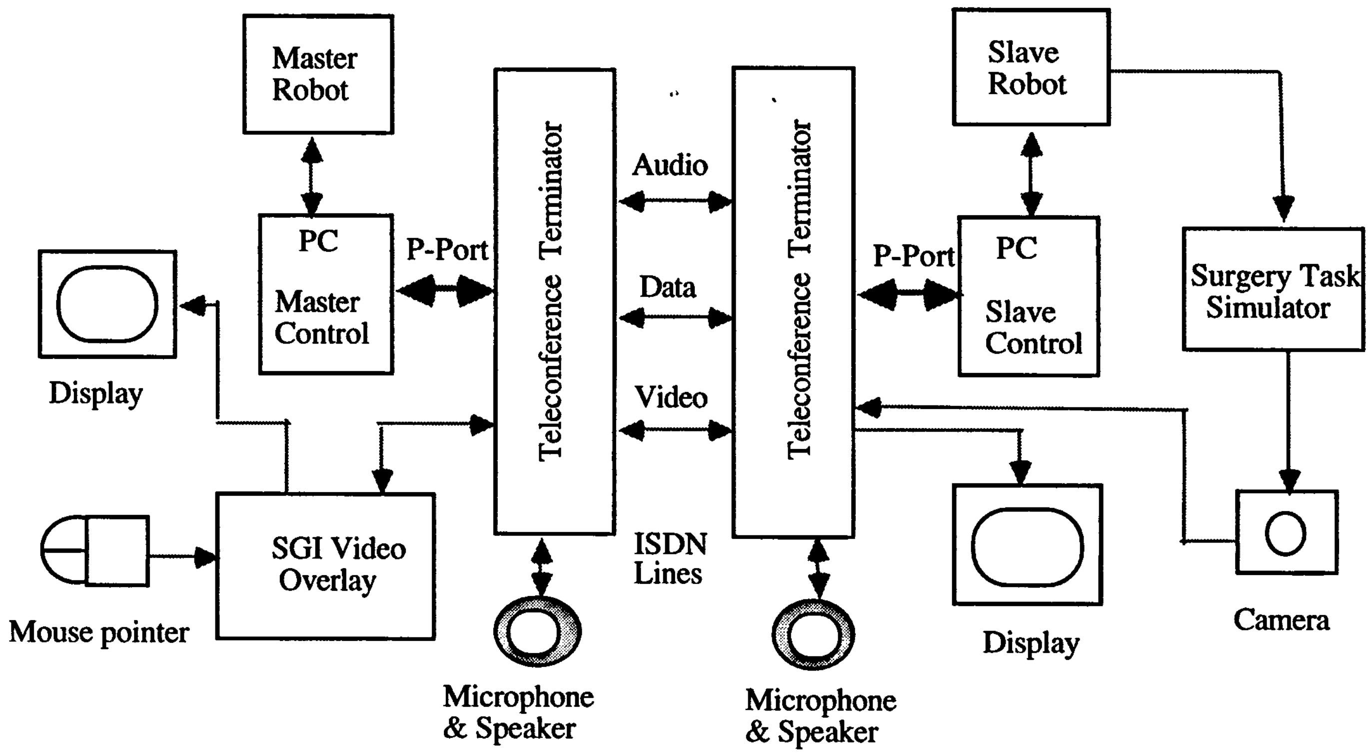


Figure 6-1: Diagram of the telerobotic surgery system in Human Machine Systems Lab., MIT

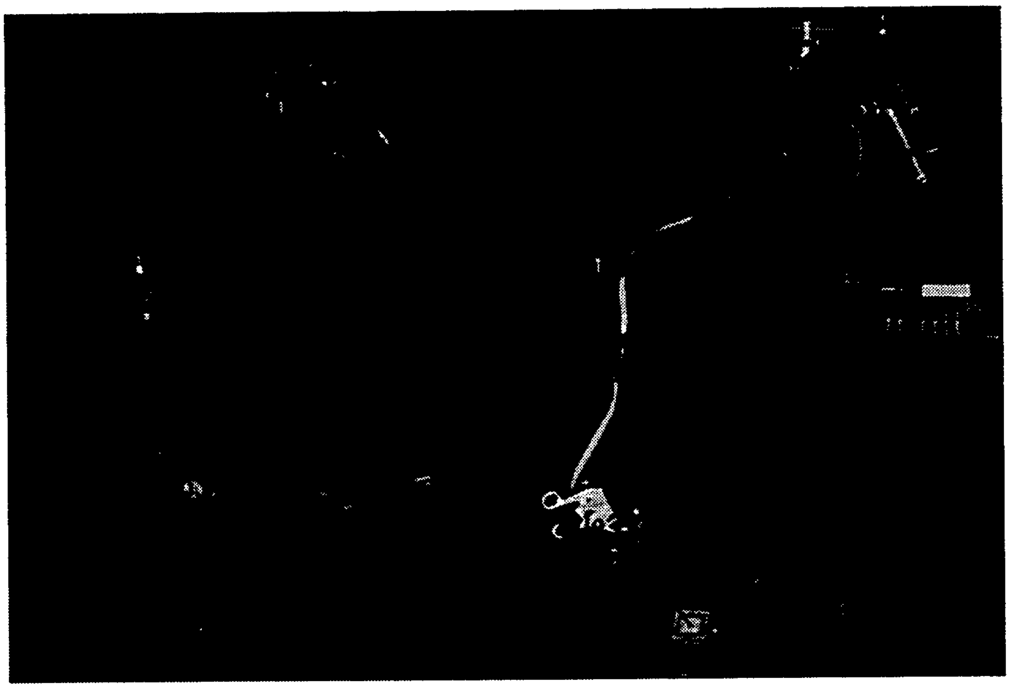


Figure 6-2: Telerobotic surgery unit. A dummy is used for task simulations.

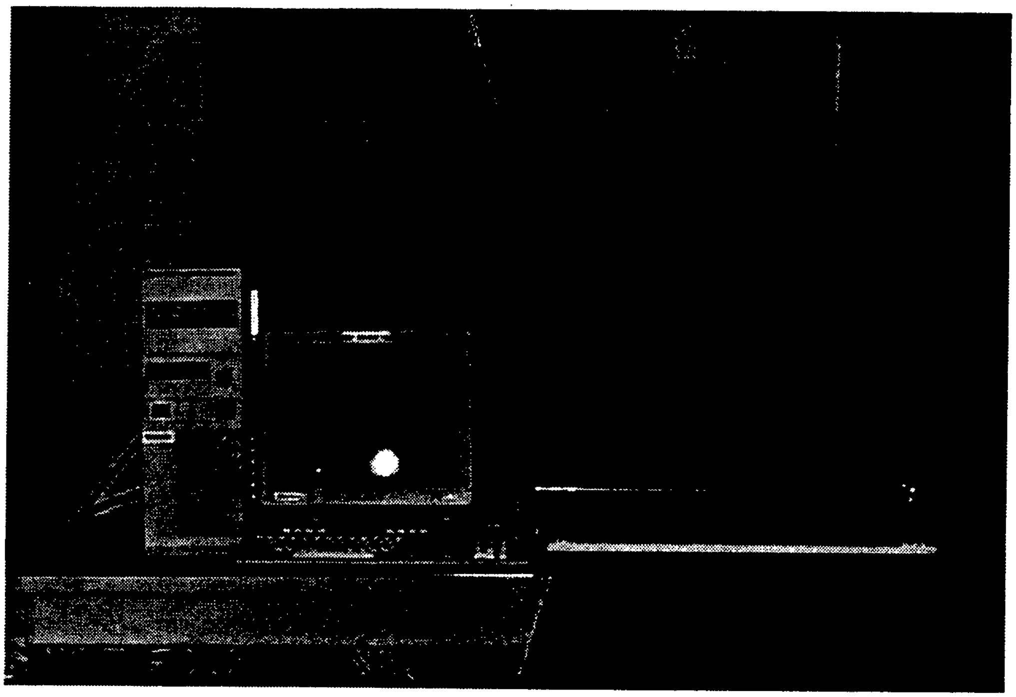


Figure 6-3: Force feedback sensing instrument of the beam

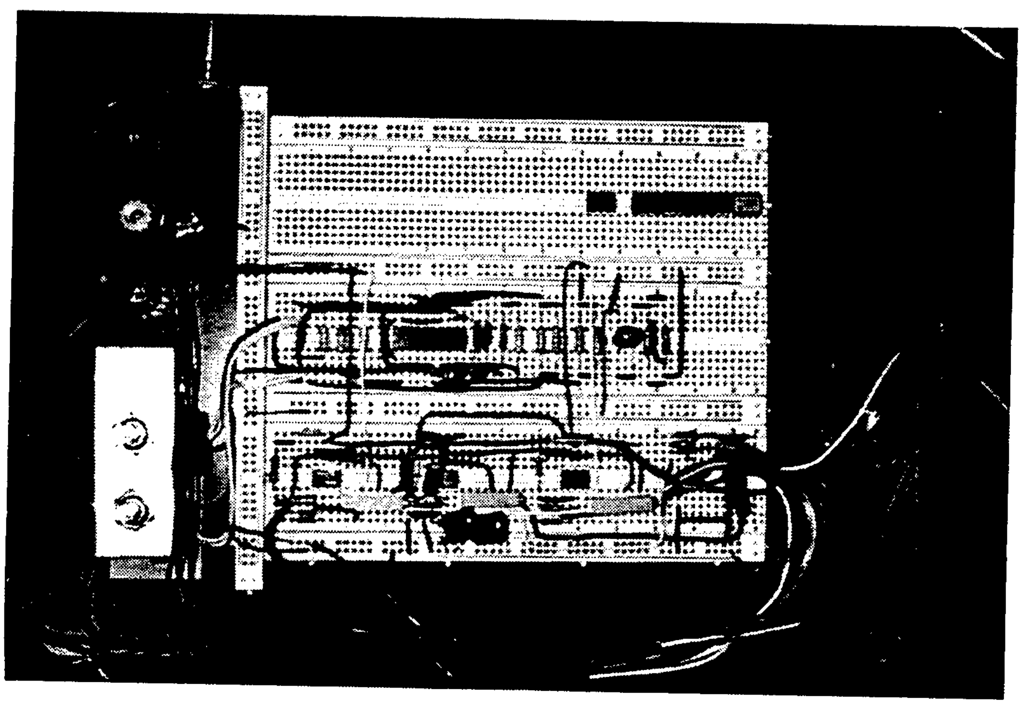


Figure 6-4: Electronic circuits for force signal processing

Chapter 7

Experiment Results and Analysis

7.1 Dynamic Responses.

Typical dynamic responses are shown in this section. In the experiments, a physical beam model was used as the task environment (see Figure 6-3). There are three different human subject experiments conducted:

1) Position drift test of passive control. During the experiments, the human subject was asked to control the master so as to make the slave contact the beam with mild force, then break contact, then make contact again, and so on. Figure 7-1 shows the response of passive control without drift compensation.

2) Passive control with drift compensation. Both the stability of force reflection and the position tracking accuracy were evaluated. Figure 7-2 shows the responses of passive control with drift compensation (1 second time delay). The upper figure (force response) was recorded when the human subject controlled the master and made the slave contact the beam and then slid on the beam with certain force from a start point to the other end of the beam. The lower figure (position response) was obtained in the same way as described in 1).

3) FSC of teleoperation. The subject experiments of teleoperation with 0.5 seconds time delay and 1 second time delay were conducted. Figure 7-3a and Figure 7-3b show the responses of FSC. The experiments were carried out in the same manner as in 2).

7.2 Comparison between passive control and FSC

1) Position drifting and comparisons between Passive Controllers with /without drift compensation.

Figure 7-1 shows the position responses of a telerobotic system with passive control but without position drift compensation. The solid line is the response of master robot, and the dash line is the response of slave robot. It is shown clearly that the slave position has a drift, which increases with time. Figure 7-1 shows the results with no time delay. As explained in chapter 4, the force term in the slave velocity command contributes to the drift in integration.

The responses of passive control with drift compensation are shown in Figure 7-2. From the responses (with 1 second time delay), the teleoperation system with passive control is stabilized, and with drift compensation the position responses have good tracking accuracy. The force signal is also smooth.

2) Comparison between FSC and Passive Control. The responses of the telerobotic system with FSC are shown in Figure 7-3. The system with FSC is stable and it has good position tracking accuracy. Comparing with the passive control approach, The telerobotic system with FSC has less damping factor, and hence dissipates less operator's energy. For the passive control approach with drift compensation needs a position scaling factor which is equal to 2.

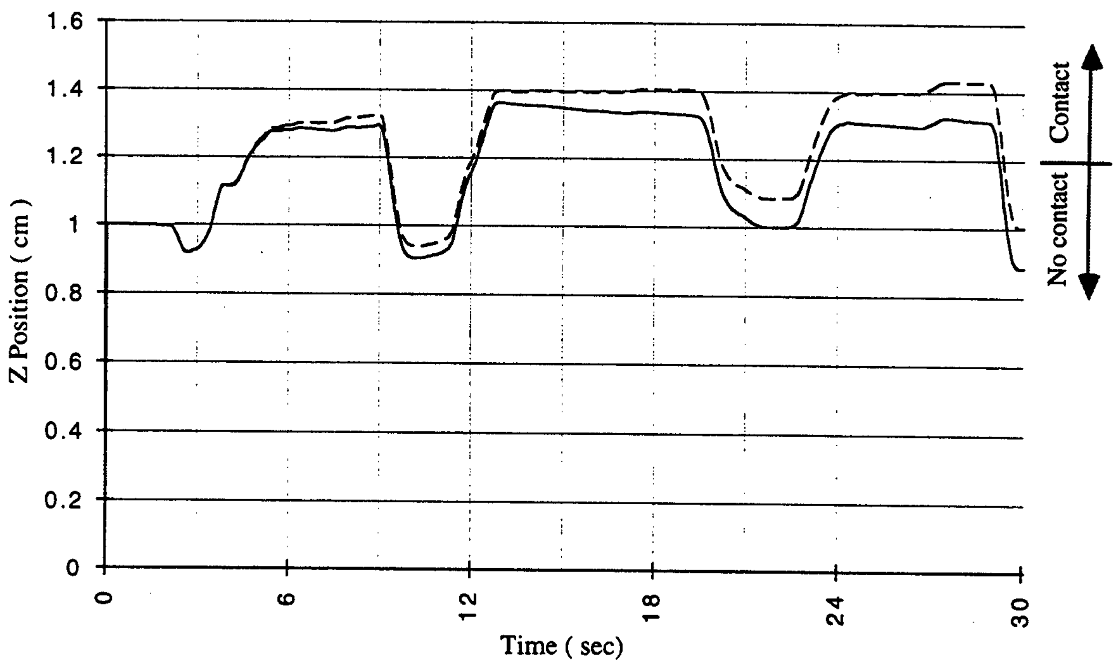


Figure 7-1: Responses of passive control without drift compensation. The solid line is master position response, and the dashed line is slave position response.

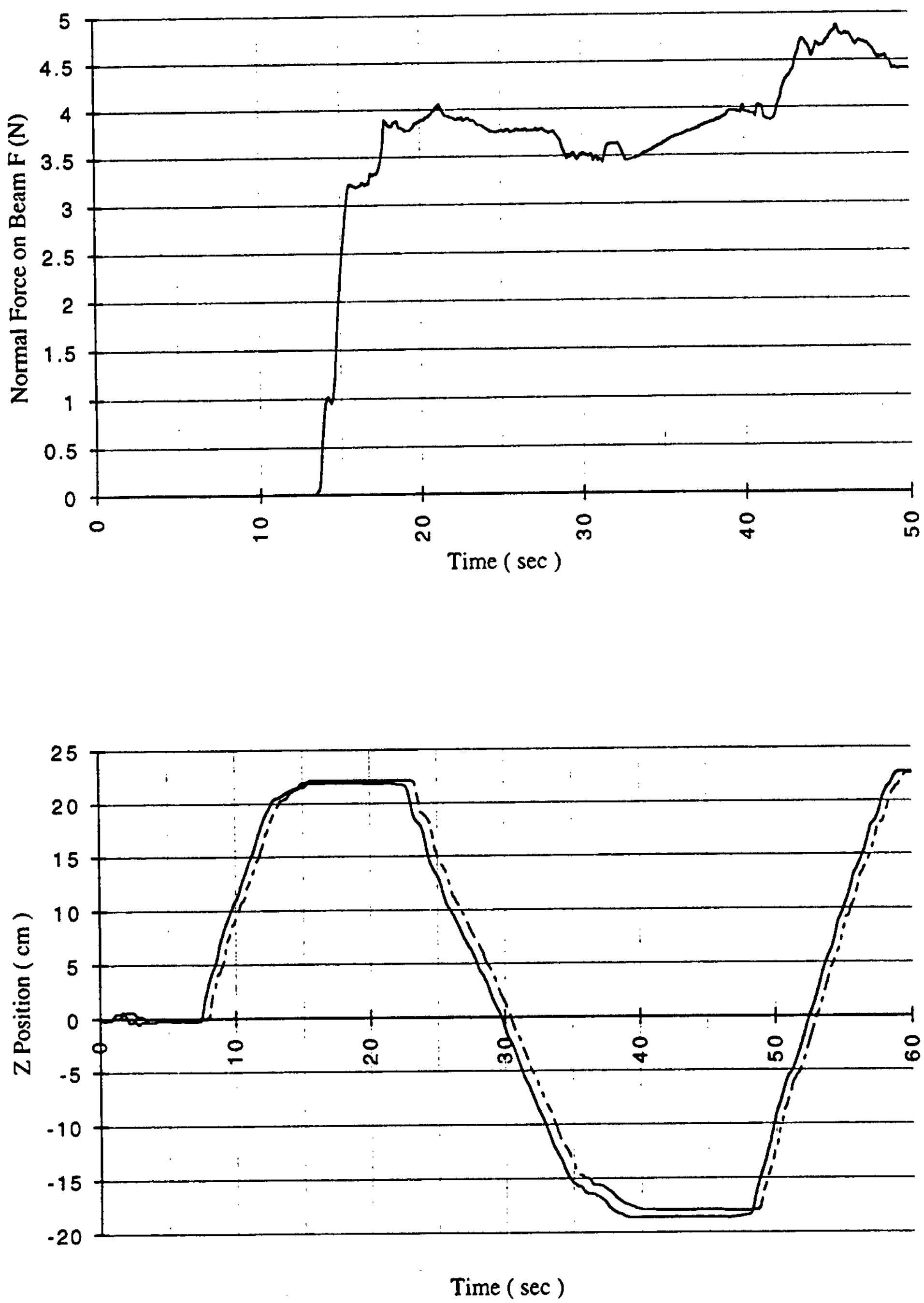


Figure 7-2: Responses of passive control with drift compensation (1 second time delay). Upper figure is force feedback from beam model, lower figure is master and slave position. Solid line is master, and dashed line is slave.

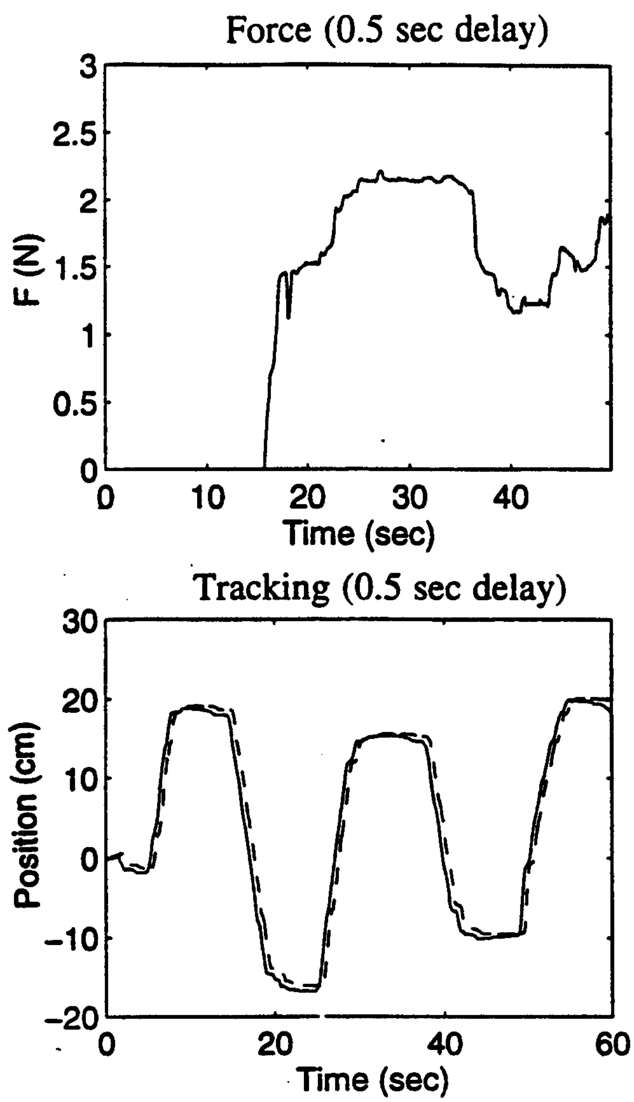


Figure 7-3a: Responses of FSC with 0.5 seconds time delay. Upper figure is force feedback from beam model, lower figure is master and slave position. Solid line is master, and dashed line is slave.

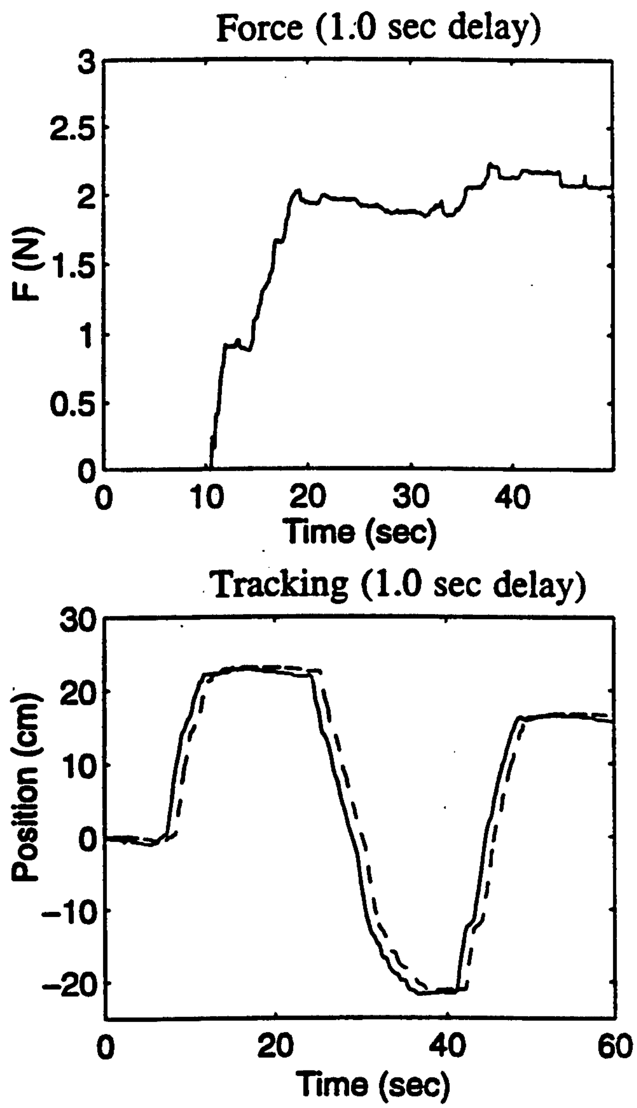


Figure 7-3b: Responses of FSC with 1.0 second time delay. Upper figure is force feedback from beam model, lower figure is master and slave position. Solid line is master, and dashed line is slave.

Chapter 8

Conclusions and Future Research

8.1 Contributions

In this thesis, the contributions can be summarized as follows:

1) A Novel stable fuzzy control approach, FSC, is proposed based on the extension of sliding control. This design provides direct stable control rule tuning in the phase plane.

2) FSC has been applied in stable force reflection control of teleoperation for the first time.

3) In passive control, a modified approach is presented to solve the position drift problem.

4) Experimental hardware and software design and implementations have resulted

5) FSC Approach is better than the conservative passive control approach in that it saves human operator's energy because passive control has big damping components and make the operator fatigued.

8.2 Future research

Telerobotics is a very broad area which covers artificial intelligence, control, robot design, communication, human-machine interaction, etc.. There are many practical and theoretical topics to be investigated. This thesis emphasizes the theoretical and experimental study of designing stable force reflecting controllers. Related to this, the following works are suggested to continue in the near future:

1) Since the passive control approaches are based on linear network theory, and nonlinearity is not taken into account during the controller design. It is worthwhile to evaluate the control performance with respect to different nonlinear tasks. FSC is expected to have better performance in dealing with a nonlinearity. It is interesting to compare both with respect to different tasks.

2) In this thesis, the typical dynamic responses give us an objective evaluation of controllers, but for overall performance evaluation one may need to conduct more subjective evaluation to compare the energy consumption, the fatiguing factor and so on.

3) There is continuing need to develop force reflecting surgical tools. It is believed that force feedback in surgical tool control is important [Revetta,1996]. In our research, the surgical tools are only position drivable.

4) Adding supervisory control mode would allow the user to switch to a different set of control parameters for different complex tasks.

5) Telepalpation should be expected in this context.

6) It is necessary to investigate how human arm locomotion affects the performance of teleoperation.

Appendix A

The Small Gain Theorem

Generally, the size of a linear map is called the operator norm induced by a vector norm. Namely the magnification power of a system H on a set of input vectors u is the norm of the output vectors $H \cdot u$ devided by the norm of the input vector. Then the gain (operator norm) of the system H induced by the input u is the maximum magnification power that the system H can exert on the set of input vector u:

$$\|H\| = \sup_{\omega} \sup_{\|\hat{u}\| \neq 0} \frac{\|H(j\omega)\hat{u}(j\omega)\|_2}{\|\hat{u}(j\omega)\|_2} \tag{A.1}$$

$$= \sup_{\omega}(\lambda^{1/2}[H^*H])$$

For a SISO system, the operator norm induced by the set of energy-bounded input is simplified into

$$\|H\| = \sup_{\omega}|H(j\omega)| \tag{A.2}$$

Thus, the operator norm of a LTI, SISO system is equivalent to the maximum amplitude of the transfer function of the system.

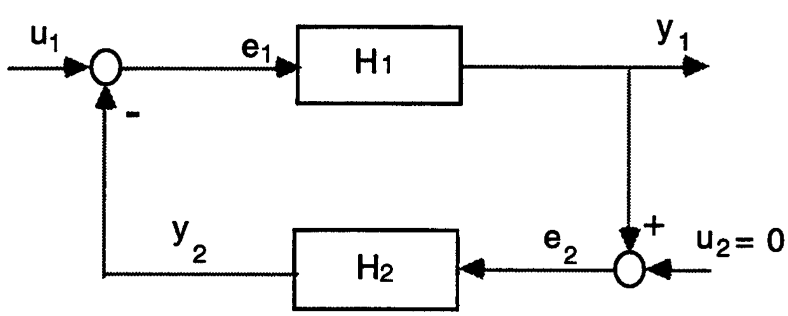


Figure A-1: The block diagram of a feedback system

In Figure A-1, H_1 and H_2 can be any kind of transfer functions (e.g. scattering matrices, impedance matrices, etc.) of a feedback system. The system stability is ensured if $(I + H_1H_2)$ remains non-singular at all frequencies, where H_2 is either a feedback controller or a system uncertainty.

The Small Gain Theorem:

If the gains (induced norms), which are chosen in accordance with the input vectors, of H_1 and H_2 satisfies

$$\|H_1\| \cdot \|H_2\| < 1 \tag{A.3}$$

then the transfer function $(I + H_1H_2)$ will remain non-singular and the system $(I + H_1H_2)^{-1}$ will be BIBO stable.

Corollary:

Given that H is small-gain but otherwise unknown, the system $(I + H_1H_2)^{-1}$ is stable iff H_1 is strictly small-gain.

Appendix B

Scattering Theory and Passive Control

For a Two port circuit, the scattering operator S is defined by,

$$f - v = S(f + v) \tag{B.1}$$

where,

$$f = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix}, \qquad v = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}$$

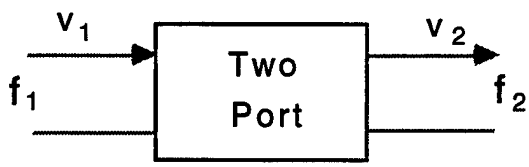


Figure B-1: A two port circuit

In the frequency domain, the scattering operator S can be expressed as a scattering matrix S(s) (assuming LTI system), where

$$f(s) - v(s) = S(s)[f(s) + v(s)] \tag{B.2}$$

Define the hybrid matrix for the above 2-port circuit,

$$\begin{bmatrix} f_1(s) \\ -v_2(s) \end{bmatrix} = H(s)\begin{bmatrix} v_1(s) \\ f_2(s) \end{bmatrix} \tag{B.3}$$

Then, one can derive the scattering operator,

$$S(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}[H(s) - I][H(s) + I]^{-1} \tag{B.4}$$

The scattering theorem:

A system is strictly passive iff $\|S\| \leq 1$

where $$\|S\| = \sup_{\omega} \lambda^{1/2}\left[s(j\omega)^* s(j\omega)\right] \quad \text{(B.5)}$$

For a communication link with a transmission delay T (second), we have

$$f_{md}(t) = f_s(t - T) \quad \text{(B.6)}$$

$$v_{sd}(t) = v_m(t - T) \quad \text{(B.7)}$$

$$H(s) = \begin{bmatrix} 0 & e^{-st} \\ -e^{-st} & 0 \end{bmatrix} \quad \text{(B.8)}$$

$$S(s) = \begin{bmatrix} -\tanh(sT) & \sec h(sT) \\ \sec h(sT) & \tanh(sT) \end{bmatrix} \quad \text{(B.9)}$$

$$\|S\| = \sup_{\omega} \lambda^{1/2}\left[s(j\omega)^* s(j\omega)\right] \quad \text{(B.10)}$$

$$= \sup_{\omega}\left(|\tan(\omega T| + |\sec(\omega T|\right) = \infty$$

Therefore the communication link is not passive.

By choosing $S = \begin{bmatrix} 0 & e^{-sT} \\ e^{-sT} & 0 \end{bmatrix}$, and considering the scaling factor B, the passive control can be derived,

$$f_{md}(t) = f_s(t - T) + B[\dot{x}_m(t) - \dot{x}_{sd}(t - T)] \quad \text{(B.11)}$$

$$\dot{x}_{sd}(t) = \dot{x}_m(t - T) + \frac{1}{B}[f_{md}(t - T) - f_s(t)] \quad \text{(B.12)}$$

Appendix c

A Physical Beam Model

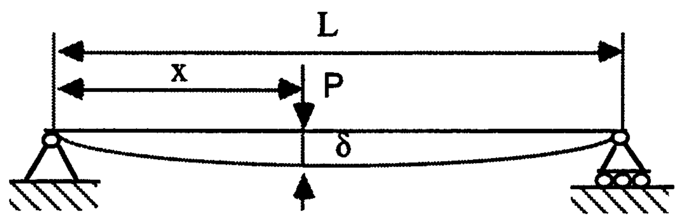


Figure C-1 A physical beam model

From mechanics of material, we can obtain the equation:

$$\delta = \frac{Px^2(L-x)^2}{3LEI} \tag{C.1}$$

where E: Young's module

I: moment of inertia of a plane area

L: length of the beam

δ : deflection

P: force exerted on the beam

Therefore, P is a nonlinear function of the tangential position and is linear to the normal displacement.

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PART II

COOPERATIVE MANIPULATION UNDER ASYNCHROUNOUS VIDEO AND CONTROL FEEDBACK

CONTENTS

LIST OF FIGURES

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Chapter 1

Introduction

During the last century we have seen an extraordinary change in the way we practice medicine, for the most part fueled by a rapid change in technology. In many cases, technology has been developed for an application outside medicine, but has then been successfully modified, transferred and then applied to the solution of a medical problem. This technology transfer is now being studied in the field of telerobotics and its application to inspection, palpation, manipulation and intervention is being considered.

Our research effort focuses on two interrelated problems:

1). Cooperative manipulation between a paramedic local to the patient and a surgeon operating through a telerobot.

2). Coping with time delay in both visual and force feedback.

1.1 Background and Significance

There are many situations where an acutely and/or critically ill patient needs to be stabilized and cared for during the triage and transport to a medical center. In the optimal case, a physician who would be riding in the ambulance would perform the initial care of the patient. Due to manpower constraints this is not possible, and necessary care in remote locations might have to be provided by individuals who have minimal or no patient management skills. Because of this, no major diagnostic or therapeutic interventions are currently possible during the initial triage at the accident site, or during the subsequent transport to the major medical center. We are proposing a telemedical acute care consultant system that addresses this problem in an effort to improve patient morbidity and mortality in these clinically suboptimal situations.

Though the use of communication systems in medicine is not new, the use of a high bandwidth audio and video link has recently been applied to the diagnosis and

treatment of the patient. Still, there are numerous situations where the bandwidth is not sufficient for the simultaneous transmission of teleoperator control signals, real time video signals and audio signals. In such a case, it is common to employ codec (compression and decompression) boards for the transmission of the video signals. Standard videoconferencing equipment over ISDN and fractional T3 phone lines currently use this technology for the video conferencing calls. This video compression and decompression imposes a time delay, and combined with the time delay imposed by the communication system produces a total time delay that adversely affects the task completion time of currently proposed telesurgical systems (explained in more detail in our previous report, Human Factors in Tele-Inspection and Tele-Surgery: Cooperative Manipulation and Time Delay, dated 9 October 1995).

Studies by Ferrell and Sheridan (1967) and Black (1970) showed that teleoperators start to use a "move and wait" strategy as the closed loop time delay increases above 0.1 seconds. In our first series of experiments (report cited above), we found that the synchronous transmission of video and controller signals (our model of 600 ms video delay plus a 600 ms communication delay) resulted in a total round trip time delay that seriously affected task performance time and resulted in a "move and wait" strategy when the surgeon operated the laparoscopic tools. In this current set of experiments we explore the hypothesis that sending the signals from a remote telesurgical setup asynchronously (sending the controller signals ahead of the video signals, which were delayed because of the compression / decompression it required) would improve controller stability and possibly favorably affect task performance by the surgical team.

1.2 Technical Terminology

1.2.1 Cooperative Tele-manipulation

Cooperative tele-manipulation is defined as the interaction (physical manipulation and audio-visual communication) between individuals working toward a common objective. Three factors are important in cooperative manipulation: objective, communication, and manipulation:

Objective

The objective of cooperative tele-manipulation in this case is initial diagnosis and surgical treatment of trauma patients during triage and transport to the medical center.

In proposed telesurgical systems the ambulance / trauma pod will be operated by two individuals. One individual will be responsible for driving the ambulance, while the other will assist the surgeon operating through a telemanipulator in the care of the patient. There are five major elements in this system: the diagnostic / therapeutic task (including the patient), the remote surgeon, the assistant, the telemanipulator and tools, and the communication channel (defined by the time delay).

The assistant will be a paramedic who will have some experience with trauma patients, but will not have the diagnostic ability, knowledge base, surgical skill or medical decision-making ability of the surgeon.

To our knowledge, no one has studied the interaction between a human and telemanipulator controlled by another human remote to the site, both collaborating on the same sensory and manipulation task.

Communication

Because the interaction of interest is between a paramedic local to the patient site and a surgeon at a remote medical center, communication is via an audio-video link that unavoidably has some amount of time delay. In the experimental setup for the Phantom arms, a digital buffer will achieve the time delay, while a hardware device performs the audio and video delay.

Three classes of signals are sent over the communication link:

1. ***Telemanipulator control data.*** The output (control signals) from one telemanipulator is sent over the communications link to the second matched telemanipulator.

2. ***Video images.*** The video signals from the laparoscope (CCD camera) are compressed, sent over a fractional T3 telephone link (3 multiplexed ISDN lines), and then decompressed for viewing.

3. ***Audio signals.*** This includes the audio from the microphone connected to the assistant.

Manipulation

The diagnostic and therapeutic tools used are the stethoscope, DPL cannula, laparoscopic surgiports, laparoscope, and laparoscopic tools (forceps, shears, blunt probe, electrocautery, and clips).

1.2.2 Synchronous and Asynchronous Transmission

In our first set of experiments we buffered the control signals while the video signal was being processed, then sent both video and controller signals simultaneously (synchronous) over the transmission link. In our second set of experiments we immediately sent the control signals over the transmission link without waiting for the video signals (which needed 0.6 second round trip for the video compression-decompression) which resulted in asynchronous transmission of video and teleoperator control signals.

1.3 Medical Terminology

1.3.1 Trauma

An important aspect of trauma management is early stabilization, diagnosis and surgical intervention. We foresee telediagnostic/telesurgery systems being used in the diagnosis and the initial therapeutic care of the patient with blunt and penetrating abdominal wounds. An initial goal is the stabilization of the patient by medical and preliminary surgical control of bleeding. Once this is accomplished, effort should then center on the judicious use of available investigative techniques to determine the need for operative intervention. By this approach early intervention can improve the morbidity and mortality associated in trauma.

1.3.2 Telesurgery

A telediagnostic communications link consists of a (ideally two way) closed-circuit video system, where the medical care consultant can pan/tilt/zoom a remote camera to observe the patient on a video monitor (and ideally the local medical care

provider with the patient) with a synchronized audio link. An augmented system allows the physician to remotely position surgical instruments, receive tactile and kinesthetic feedback, and with the manipulative assistance of the local provider, perform diagnostic and preliminary surgical intervention on the patient.

The type of telesurgical link used is dependent on the communication links available at the site. Alternatives include T1 (1.544 Megabits/sec), fractional T1 (0.384 Megabits/sec), T3 (45 Megabits/sec), satellite transmission, and microwave link.

There are various barriers to implementation of telemedical systems. Foremost are the issue of liability for the surgeon, the paramedic, and the manufacturer of the equipment. There are also the high communication costs associated with long distance telecommunication rates or satellite time, in addition to the initial costs of improving outdated equipment and phone lines. In most cases, there are no standards of care or reimbursement mechanisms in place for such telesurgical services.

1.3.3 Minimally Invasive Diagnostic Procedures

Peritoneal Lavage

Diagnostic peritoneal lavage (DPL) continues to play an important diagnostic role in the evaluation of blunt abdominal trauma. There are three methods of performing a DPL. In the "open" technique, the surgeon first makes an incision through the skin, subcutaneous tissue, linea alba and peritoneum before inserting the cannula into the peritoneal cavity under direct vision. In the "semi-open" technique, an incision is made through the skin, subcutaneous tissue, and linea alba before the cannula is inserted through the peritoneum. In the "closed" technique, the cannula is inserted through all the layers of the abdomen via a blind stab. Once the cannula is inserted, aspiration for free intraperitoneal blood is generally recommended followed by a lavage of 1000 cc of normal saline. Peritoneal fluid is then aspirated and analyzed.

Laparoscopy

Dr. Isaac Ott (a Russian Gynecologist) first reported laparoscopy in 1910; he used a speculum to view the abdominal viscera in a dog. Kelling, in 1923, reported on the use of a cystoscope for the same procedure. Gazzaniga (Gazzaniga, 1976) first proposed the

use of laparoscopy in the diagnosis of abdominal trauma. The introduction of the laparoscopic cholecystectomy 8 years later started the latest surge in interest in laparoscopic procedures.

There is also renewed interest in the use of laparoscopy in the evaluation of trauma patients. Earlier studies had been performed before its widespread use in general, orthopedic, and gynecological surgery, which has resulted in great improvement in instrumentation and video quality. Recently Ivatury (Ivatury et al, 1993) evaluated the use of laparoscopy in penetrating abdominal trauma, and found that the diagnostic accuracy was excellent for hemoperitoneum, solid organ injuries, diaphragmatic lacerations, and retroperitoneal hematomas, but it had a poor sensitivity to hollow viscus injuries. While other studies support this contention, further investigation of laparoscopy for evaluation of trauma is needed to assess its accuracy.

In the experiment reported here we used the following laparoscopic equipment: DPL cannula, laparoscopic surgiports, laparoscope, and laparoscopic tools (forceps, shears, blunt probe, electrocautery, and clips).

1.4 Summary of this thesis

1.4.1 Research Objectives

The long-term goal of our project and many others is the provision of practical telesurgical systems that will assist the medical care provider (who might have limited medical care experience) in the management of a medical emergency (including surgical intervention) at a remote location. Such an event might occur in both civilian and non-civilian situations in locations such as battlefields, natural disasters, research stations in the Antarctic, and NASA space missions, among others.

Our specific research project is concerned with evaluating telesurgery from a human factors engineering viewpoint. In particular it focuses on two interrelated problems:

1). Cooperative manipulation between a paramedic local to the patient and a surgeon operating through a telerobot.

2). Coping with time delay in both visual and force feedback.

In our first series of experiments (previously cited report), using synchronous video and control signals, we found that the time delay made operation of the laparoscopic tools by the surgeon extremely difficult.

In the experiments reported here we asked the question: Does sending the signals from a remote telesurgical setup asynchronously (sending the controller signals ahead of the video signals, which were delayed because of the compression / decompression it required) improve controller stability and favorably affect task performance by the surgical team.

Chapter 2

Research Methodology

In section 2.1 we will explain the medical issues important in the remote management of the trauma patient. We discuss our experimental apparatus in section 2.2. In section 2.3 we identify the important laparoscopic surgical procedures applicable to our system, followed by a discussion of the experimental tasks in section 2.4.

2.1 The Telesurgical System to be Modeled

In the proposed telesurgical system the ambulance / trauma pod will be operated by two individuals. One individual will be responsible for driving the transport, while the other will assist the telemanipulator in the care of the patient. This is similar in structure to a standard ambulance team setup. The five major factors mentioned earlier (the diagnostic / therapeutic task, the remote surgeon, the assistant, the telemanipulator and tools, and the communication channel) interact as illustrated in Figure 2.1.

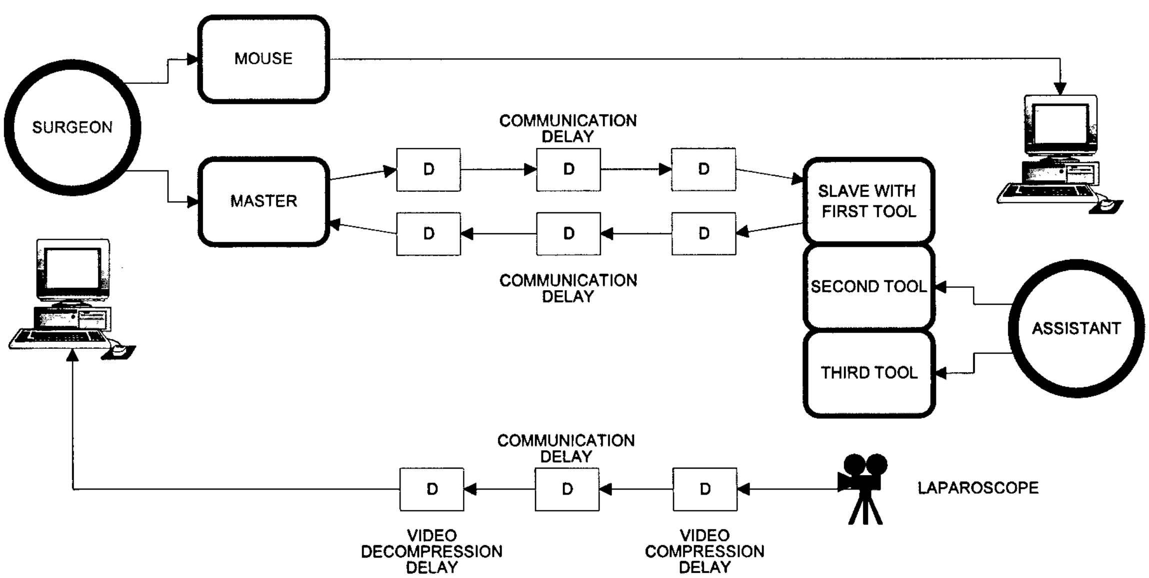

Figure 2.1 Telesurgical System

2.1.1 Telesurgical System: Diagnostic / Therapeutic tasks

The *diagnostic* task is a function of the current state of the patient. Use of the telemanipulator must be appropriate to the nature of the trauma, yet pose a minimum of complexity and potential harm to the patient. Laparoscopy, a minimally invasive procedure, is safer and more easily performed over a communication line than an open surgical procedure. Therefore the authors feel that a realistic telediagnostic goal would be to assist in location of the source of hemorrhage from a blunt and/or penetrating traumatic injury. This type of diagnosis is extremely important in the trauma setting, as the majority of patient deaths on the battlefield result from bleeding prior to arrival at a surgical facility.

The damage caused by blunt and/or penetrating injury can be subdivided into two major types, internal and external. The assistant can identify external hemorrhagic injuries with or without assistance by the remote surgeon, who would as necessary assist through a simple video hookup. Because of the location of the injury, internal hemorrhagic injuries are more difficult to evaluate and would require an invasive procedure for diagnosis. A telemanipulator controlled laparoscope and / or blunt probe is a minimally invasive system that would be a useful diagnostic tool for internal abdominal injuries. The tools that are required for such a system would be a telemanipulator-controlled laparoscope and a telemanipulator-controlled blunt probe.

The *therapeutic* task in the care of the trauma patient would be to stabilize the patient before and during transport to a medical center where more definitive diagnostic and therapeutic procedures can be initiated. In the case of the trauma patient, an important and potentially life saving therapeutic maneuver would be to stop the bleeding from external and internal sites. Again a surgical telemanipulator system would be useful for internal hemorrhage and would require a telemanipulator-controlled laparoscope, telemanipulator-controlled hemostat, telemanipulator controlled clip applicator, and a telemanipulator-controlled scissors. A laparoscope would allow the surgeon to look for internal hemorrhage. The hemostat would be used as a blunt probe to move internal organs and to temporarily occlude any bleeding vessels. A clip applicator would be used

to further stabilize a bleeding vessel and allow the hemostat to be removed from the abdomen. The scissors would be used to cut adhesions for a better view of the surgical field.

2.1.2 Surgeon

The role of the surgeon in this case is to make an initial diagnosis and decision on what therapeutic intervention is needed to stabilize the patient. The surgeon will be constrained by the fact that the patient is at a remote site, but will have the services of the telemanipulator and the assistant who is with the patient. The surgeon would control both the master end of the telemanipulator and a mouse or other device for indicating locations in the video screen of the assistant.

2.1.3 Assistant

The assistant would most likely be a paramedic who will have some experience with trauma patients, but would not have the diagnostic ability, knowledge base, surgical skill or medical decision making ability of the surgeon. Depending on whether the setting is civilian or military, the paramedic for each case is usually chosen from a group of similarly qualified individuals, based on who is working at the time of the trauma, and which available unit is physically closest to the patient. Each of the paramedics will have different strengths and weaknesses, based on innate skills, personality and training. The assistant controls surgical tools not under control by the surgeon, as indicated in Figure 2.1.

2.1.4 Telemanipulator and Tools

The telemanipulator and tools are important in enabling the surgeon to diagnose and treat the trauma patient in the remote environment. As mentioned above, a minimally invasive technique using a laparoscope and laparoscopic tools is probably the best method of achieving our diagnostic and therapeutic goal for the remote trauma patient. One needs to be able to control a laparoscope for viewing, and be able to manipulate a hemostat (to be used as a blunt probe and to grab intra-abdominal contents), a scissors and a gripper / clip applicator (for clamping the bleeding vessel).

2.1.5 Telesurgical System: Time Delay

In a telesurgical system one is faced with two types of time delays: (1) delay associated with the transmission of the signals from the teleoperator over a communication link, and (2) the delay due to the video compression and decompression due to a communication bandwidth.

The transit time for signals sent over communication channels depends on the medium (e.g. ISDN, satellite) and the traffic over that medium. With an ISDN setup, the typical round trip delays are in the order of 600 ms (Zydacron, 1996). The distance can also be a factor. Researchers reported a 1.4 second round trip delay in a teleoperator connection between Tokyo and Washington, D.C. (Mitsuishi, 1995).

There is also a delay associated with the video compression and decompression needed when unlimited bandwidth is not available. Current video conferencing equipment that uses ISDN lines (fractional T3, which is three multiplexed ISDN lines) requires approximately 300 ms for the video compression and subsequent decompression for one way transmission. The components of these delays are shown in Figure 2.1.

2.2 Experimental Apparatus

Our experimental set-up is intended to model the telesurgical system described in the previous section. In particular, our set-up for the asynchronous experiments is as shown in Figure 2-1. The components were designed and constructed during the initial stages of our project and explained in more detail in our previous report, Human Factors in Tele-Inspection and Tele-Surgery: Cooperative Manipulation and Time Delay, dated 9 October 1995.

2.2.1 Surgical Tool Handle

In order to make the working environment as realistic as possible, we used modified laparoscopic tools of the type currently being used in the operating room. The test surgeon operated these tool handles just as he would in normal laparoscopic surgery. . Our modified tool handle is seen in Figure 2.2.

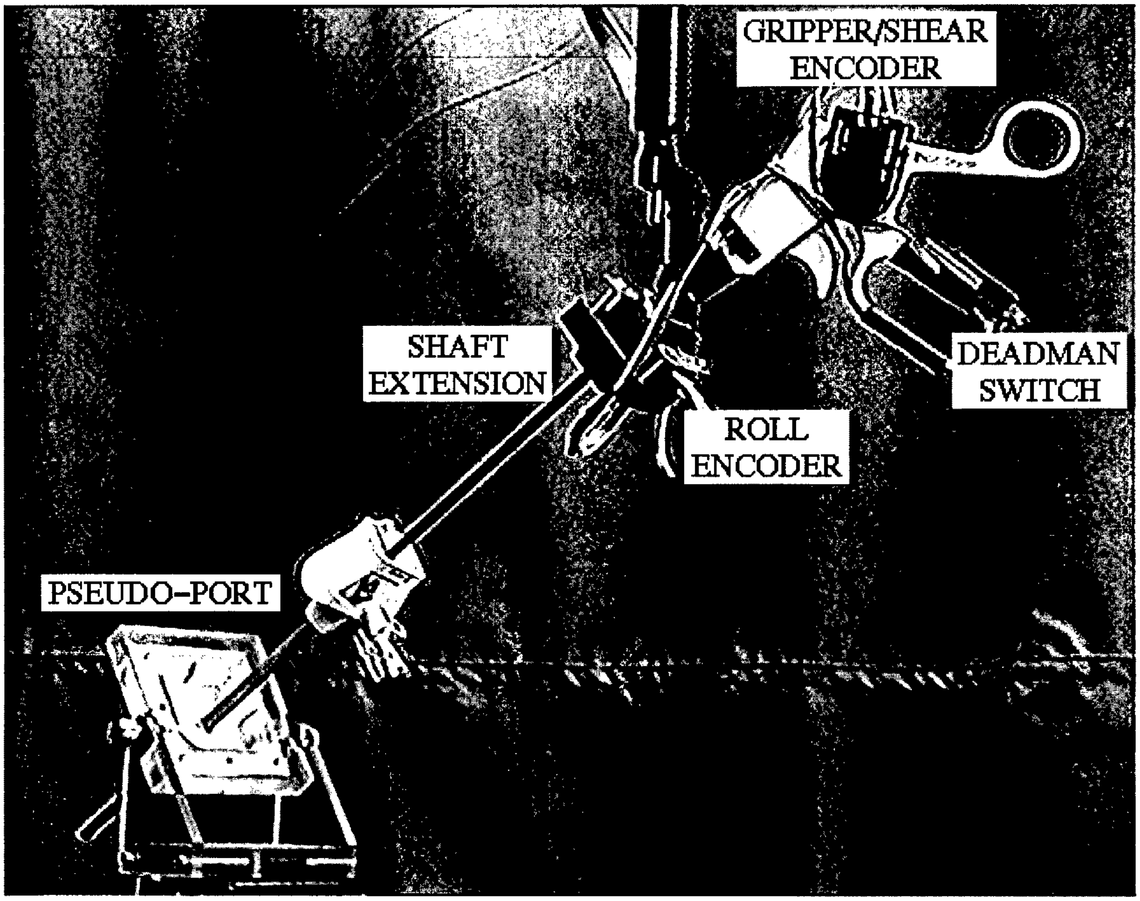

Figure 2.2: Modified tool handle for master telemanipulator

2.2.2 Paired Telemanipulators

The telemanipulators used were paired PHANToM manipulators that were initially developed as a force-reflecting interface. One of the phantoms, operated by the test surgeon, was used as a master on which the tool handle was fixed (Figure 2.2). The second manipulator (Figure 2.3) operated as a slave (to which the other end of the laparoscopic tool was attached). The control software used was developed as part of the project (Hu et al, 1996) and is an attached report.

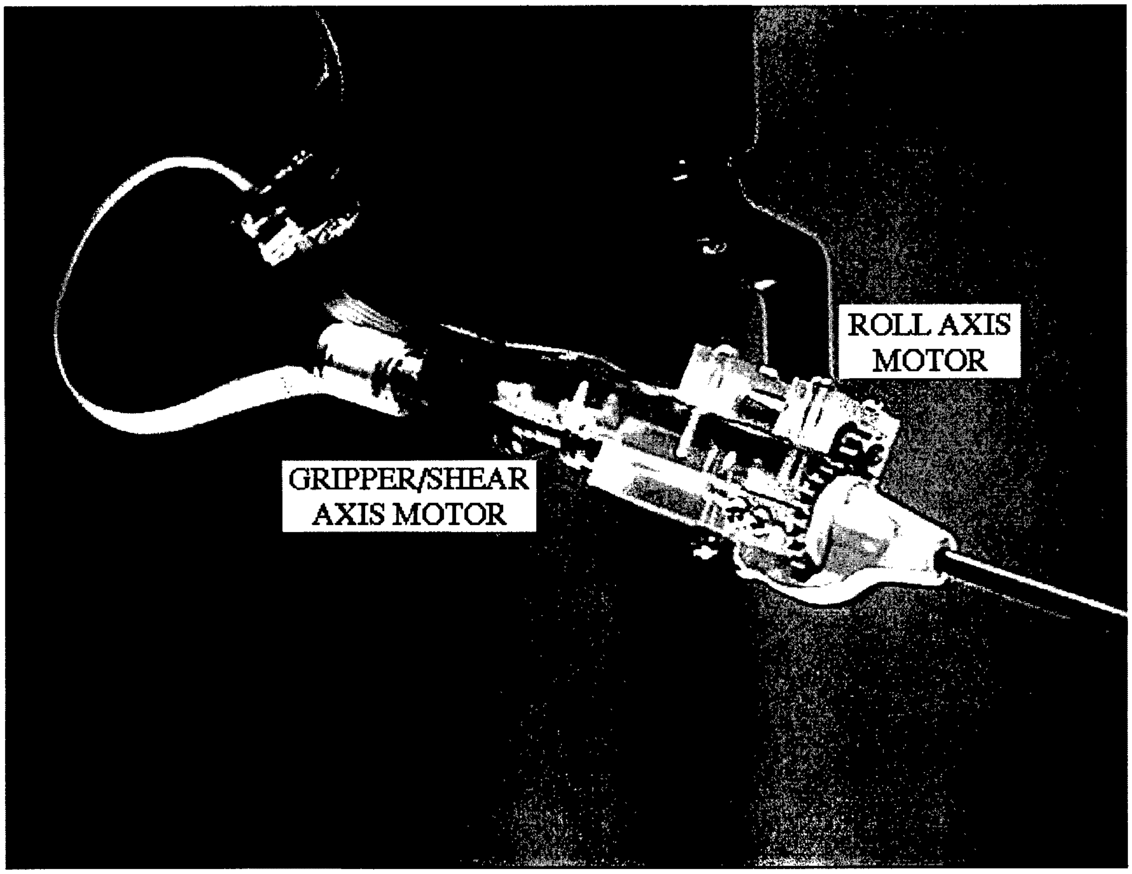

Figure 2.3: Modified tool tip on slave telemanipulators

2.2.3 Modified Laparoscopic Tools

In order to provide as much realism as possible, the laparoscopic tools used were actual tools used in the operating room which were modified for our use. The tool handle was detached from the tip and attached to the master amnipulator. Because the PHANToM telemanipulator had only three translational degrees of freedom, a single rotational degree of freedom (around the tool axis) was mechanized (see report attached above) and is shown in Figure 2.2. For the slave manipulator, the tool tip was modified to provide a roll axis and is attached to the slave phantom using the gimble wrist end of the phantom. This attachment to the slave manipulator is shown in Figure 2.3 while the various modified tools and their linkages are shown in Figure 2.4.

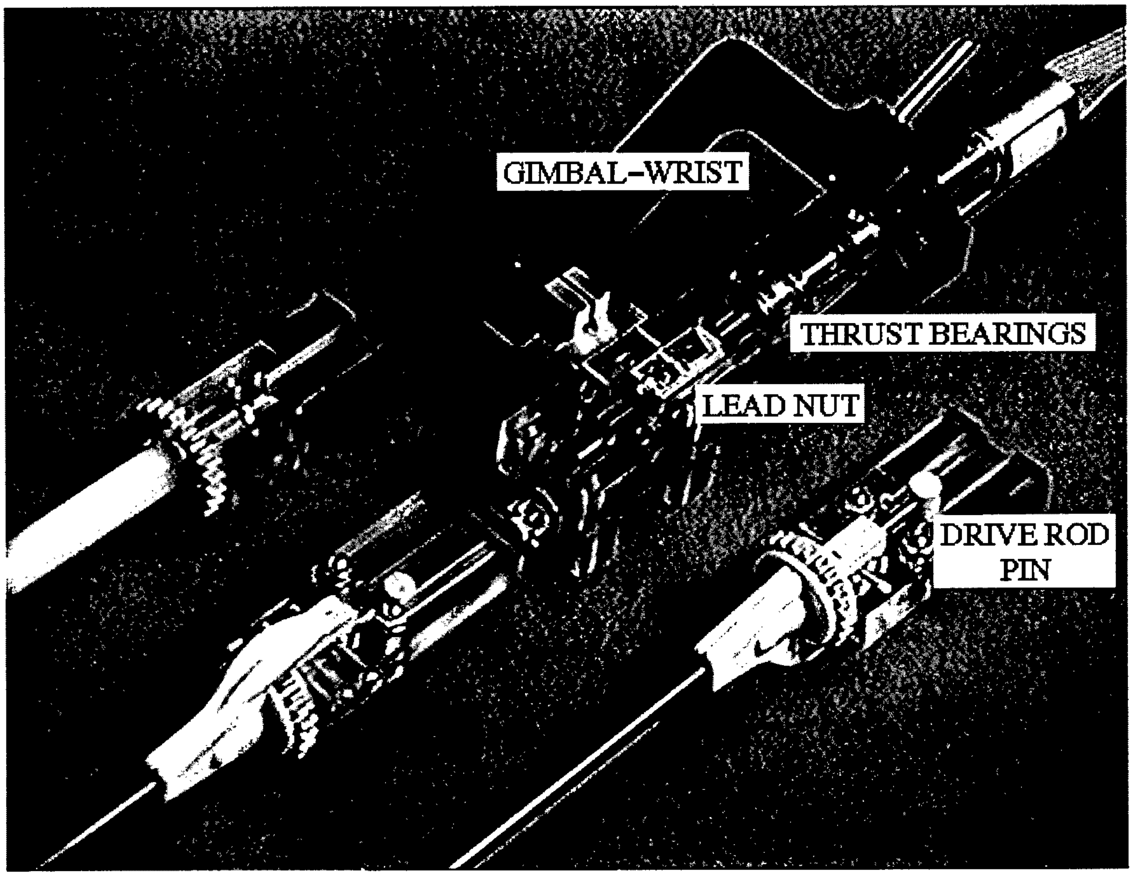

Figure 2.4: Modified laparoscopic tool

The modified laparoscope and the various tool tips used in our experiments are shown in Figure 2.5.

2.2.4 Audio / Visual System

The audio / visual system consisted of microphones and headsets, cameras and displays and a two-way communications setup. Thus both audio and video were available to both the surgeon and assistant. We used two matched headphone / boom microphone systems connected through a pre-amp / amplifier to the audio delay boards. The camera at the patient end was integral to the laparoscope itself.

An audio / visual delay system was used to generate the audio and visual delays to model the transmission line and video compression / decompression delays. We used a

Prime Image A/V mainframe with two video delay boards and a 2 channel audio board that was connected to our camera, monitors and audio communication equipment.

The video images were recorded with a Video Hi-8 recorder and routed to the two video monitors and VHS recorder through a Silicon Graphics Galileo video board.

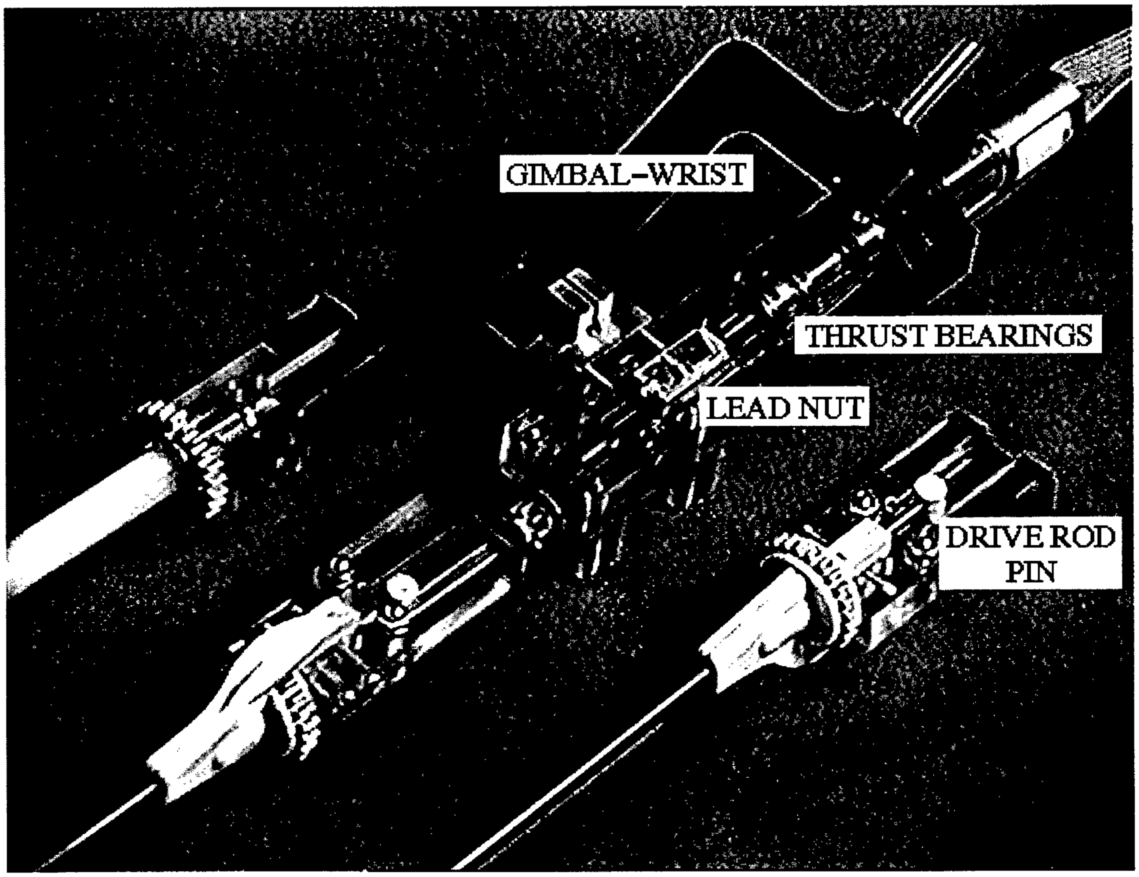

Figure 2.5: Modified Laparoscope and tool tips

2.2.5 Laparoscopic Test Bed

We used the same surgical laparoscopic simulators designed and constructed for our first series of experiments. The simulator used for our experiments was modeled after laparoscopic training simulators (Bailey et al, 1991 and Muntzer, 1992) which has four surgical incision sites for trocar insertion and has an opaque side wall for recording the experiments with a camcorder. This is shown in Figures 2.6.

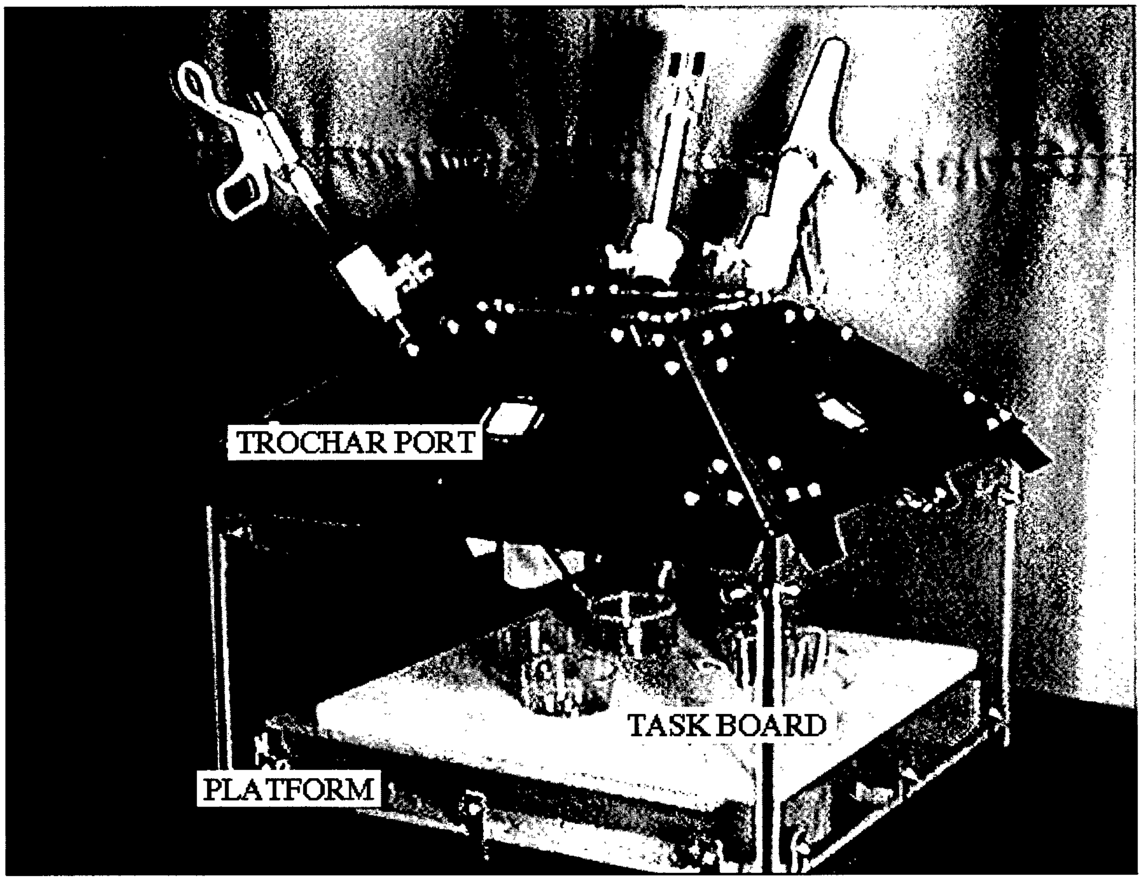

Figure 2.6: Exterior view of simulator

We also modified a resuscitation mannequin for a more visually realistic laparoscopic model for demonstration purposes (Figure 2.7).

2.2.6 Video Overlay System

In our experimental setup, the surgeon operated a mouse pointer that was superimposed over the image from the surgical site and was used by the surgeon as a visual tool to direct the actions of the assistant. This video overlay was generated by a Silicon Graphics Indigo2 Extreme workstation using a Galileo video card.

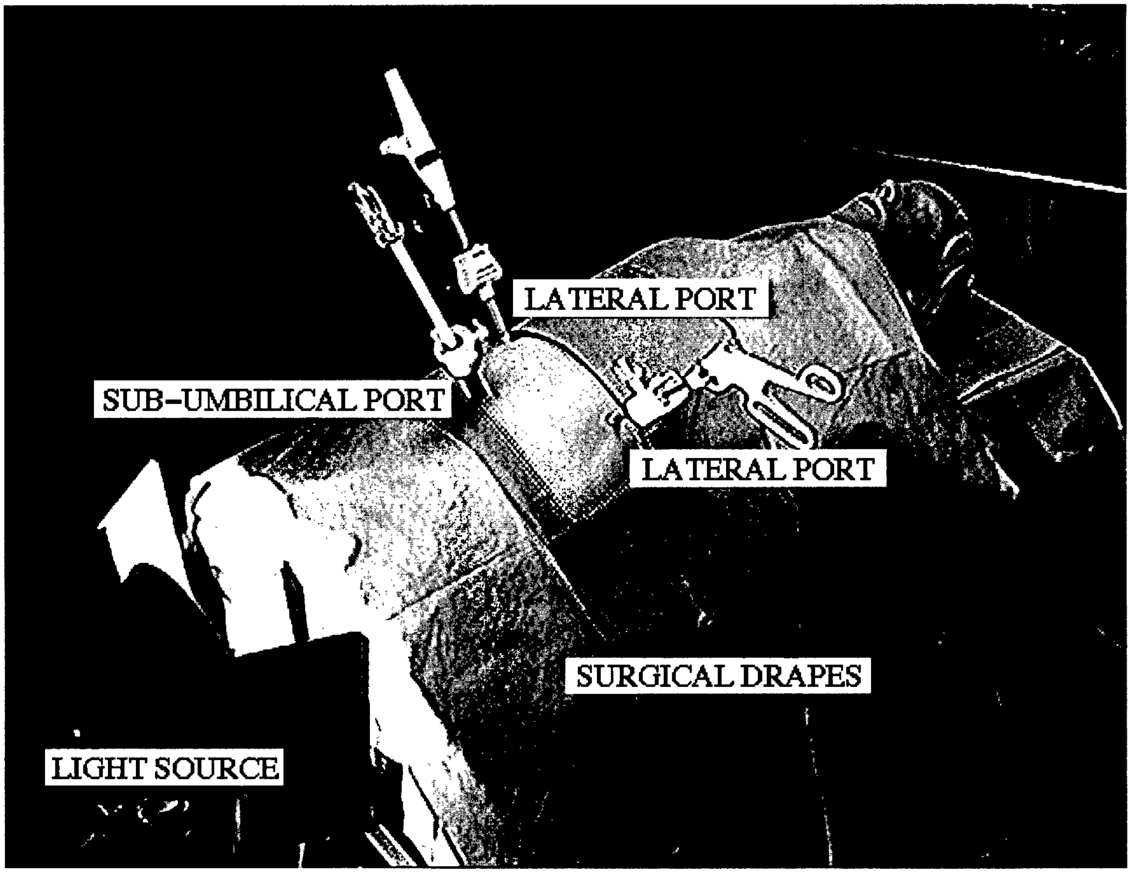

Figure 2.7: Demonstration simulator

2.3 Normal Laparoscopic Surgical Procedure

2.3.1 Identification of "Abdominal Contents"

The laparoscope is manipulated inside the peritoneal cavity where the contents are visually inspected for signs of damage. If a surgically correctable problem is identified then the procedure continues with insertion of additional surgiports for the laparoscopic tools. The hemostat is used to move and manipulate the abdominal organs in order to give the physician a better view of the abdominal contents. The ability to move and view contents of the simulator was studied and presented in the attached report.

2.3.2 Insertion of Surgiports for the Laparoscopic Tools

Initially two additional surgiports are inserted with visual inspection of the insertion sites from within the peritoneal cavity using the laparoscope. This is to prevent trauma to the peritoneal contents from the surgiport trocars.

2.3.3 Insertion and Removal of Laparoscopic Tools

The necessary laparoscopic tools are inserted into the surgiport under visual observation.

2.3.4 Visual Localization of "Bleeding Site"

Initially three hands are utilized for the identification of the bleeding site. One hand operates the laparoscope, a second hand operates the blunt probe, while the third hand operates the forceps. The surgeon has the option of quickly switching control to the tool that he wants to manipulate (foot switch), which gives him better control over the procedure.

2.3.5 Blunt Dissection to Isolate "Bleeding Site"

Once the site of bleeding is localized, then surgical manipulation of the site is needed for the isolation of the bleeding vessel. This is to insure that important structures (e.g. nerves) adjacent to the bleeding vessels are not inadvertently damaged during permanent control of the bleeding vessel. Initial control of bleeding is necessary and is temporarily achieved with a forceps applied to the general area.

2.3.6 Permanent Control of Bleeding

If the bleeding vessel is small, then the vessel can be cauterized electrically. The electrocautery is applied to the forceps that held the bleeding vessel. If the vessel is large, then surgical clips are applied to mechanically occlude the bleeding vessel. This is standard surgical practice when working with blood vessels that are no longer needed or are bleeding and permanent control of the bleeding vessel is necessary. If the vessel is an artery that is important for blood supply to an organ or region, then the vessel would initially be occluded for control and later repaired in a more definitive procedure.

2.4 Experimental Surgical Tasks Used

2.4.1 Grasp and Transfer Experiments

This experiment evaluated the ability of the surgical team to control the hemostat and to work together to perform a task. In this task the assistant picked up a first paper clip with the hemostat, passed it to the person operating the second hemostat, who then deposited it into the second cup (Figure 2.8). This proceeded until all six clips were transferred from the first to the second cup. The performance time was defined as the time it takes for the surgeon – assistant team to transfer 6 clips from one cup to the other.

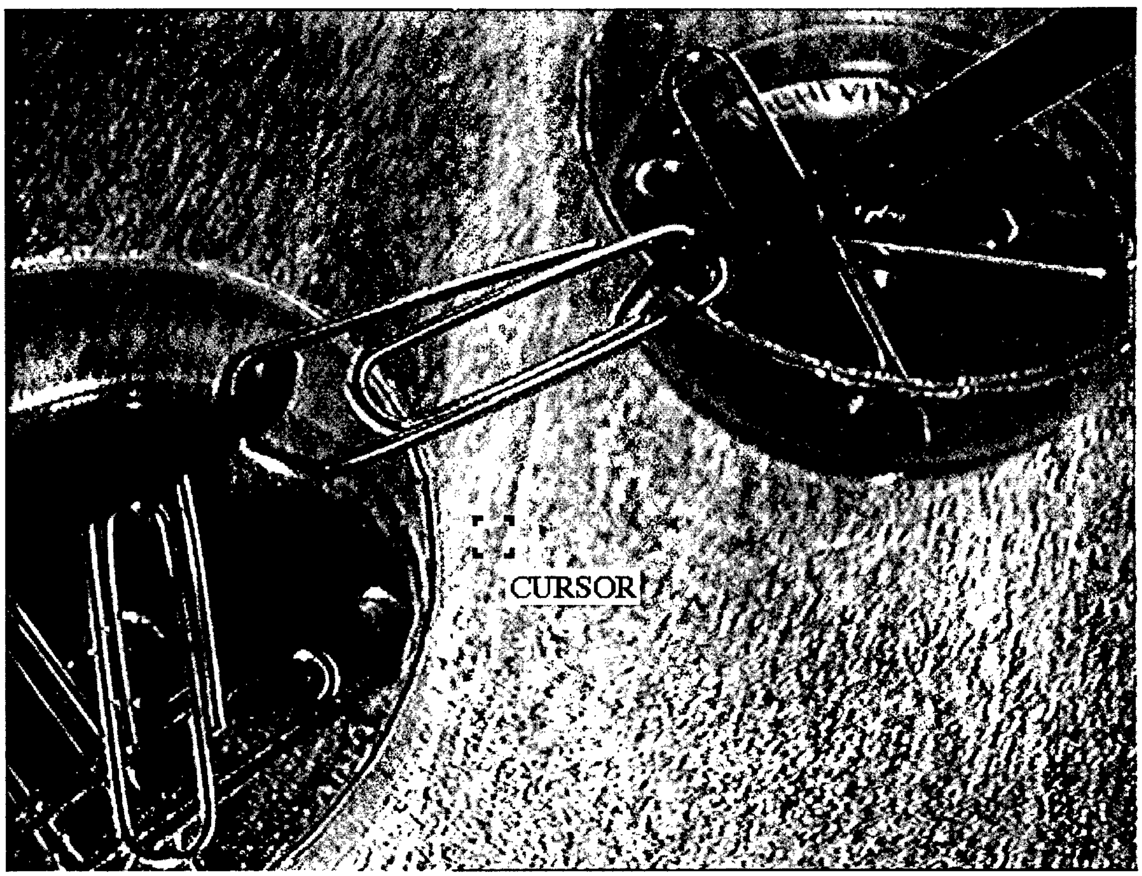

Figure 2.8: Grasp and Transfer Experiment

2.4.2 Hemostasis

In this experiment we evaluated the use of the clip applicator / hemostat and the scissors by the surgical team (surgeon and assistant). We staredt with a model of the neurovascular bundle (a nerve, artery and vein usually travel together) made up of tan, blue and red rubber bands. If a blood vessel is damaged and is bleeding, the goal of the surgical team is to isolate the bleeding vessel without damaging the adjacent nerve and blood vessel. Once the bleeding vessel is isolated and the bleeding controlled it is clipped (stapled) shut and the redundant vessel is cut. The task completion time was measured as the time it took the team to correctly place the hemostat / clipper completely around the related vessel (with the exclusion of adjacent structures), clip off the vessel, and then to cut the redundant vessel with the scissors. This experiment is shown in Figure 2.9.

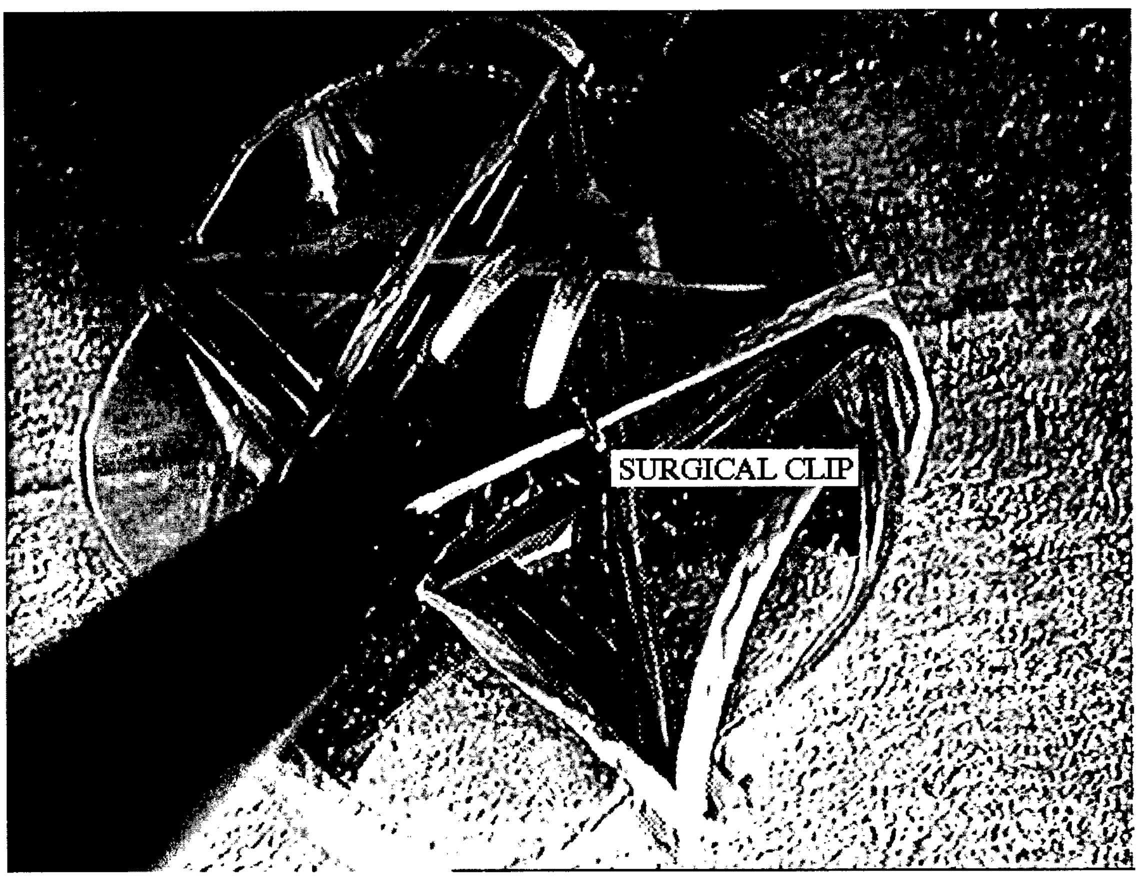

Figure 2.9: Hemostasis Experiment

2.5 Experimental Subjects

The combination of two major experimental setups, four surgical tools and six combinations of time delays resulted in thirty experiments that were recorded for each of the six subjects. The test surgeon throughout the experiments was an experienced emergency room physician and anesthesiologist. The assistants were engineering graduate students. These were the same individuals that were tested in the first set of experiments run the previous year.

2.6 Data Recording

The experiments were recorded to a VCR deck using a high fidelity Sony Camcorder. The author later reviewed these videotapes and the task completion times were recorded for each of the individual experiments.

Chapter 3

Results and Discussion

The results for the individual tool combinations for each experiment are presented and discussed in the following sections of this chapter, Figures 3.1 –3.4.

In general, we found that when the surgeon operated the laparoscope there was a slight improvement in task completion time when the task was performed with asynchronous (as compared to synchronous) video and control feedback signals. When the surgeon used any of the other tools, we found a dramatic improvement in task completion time when the signals were sent asynchronously, for both the 0.6 second and 1.2 second delays. A summary of the average task completion time for each of the experiments and tool combination is presented in the Appendix.

3.1 Grasp and Transfer Experiments

There were two physician / assistant tool combinations for this experiment. In the first scenario, the physician operated the scope through the teleoperator while the assistant operated the two hemostats. In the second scenario, the surgeon operated one of the hemostats while the assistant operated the laparoscope and the other hemostat. As in our first series of experiments, we found that task completion time is lowest (better performance) when the surgeon operated the laparoscope rather than operating one of the hemostats. We found this to be the case in all six experiments in which we varied the time delays for both the video signals and the controller signals.

In our second set of experiments we studied the effect of asynchronous video and control signal transmission on task completion time with various time delays. Our results, which are presented below for each time delay, surprisingly showed a significant improvement in task completion time with asynchronous (as compared to synchronous)

signal transmission. Apparently it was better to have force feedback sooner even if it meant it was not synchronized with the video. A detailed explanation follows:

3.1.1 Experiments with no transmission time delay in telemanipulation

In the experiments with no transmission time delay the controller signals were transmitted between teleoperators without any delay while the video signals were transmitted with a 0.6 sec round trip delay (inherent in the video compression and decompression algorithms). In our first set of experiments we held the control signals while the video signal was processed and then sent both video and controller signals simultaneously (synchronous) over the transmission link. In our second set of experiments we immediately sent the control signals over the transmission link without waiting for the video signals (which needed 0.6 sec round trip for the video compression-decompression) which resulted in the asynchronous transmission of video and teleoperator control signals.

Physician operating the laparoscope

In this experiment the physician operated the laparoscope using the teleoperator while the assistant local to the patient operated the two hemostats. In the synchronous experiments (both video and controller were transmitted together with a 0.6 sec round trip delay) the average completion time was 16.0 seconds. In the asynchronous experiments (the controller signals were transmitted with no time delay while the video signal was sent with a 0.6 sec round trip delay) we had an average completion time of 13.2 seconds. These experimental results show a 17% improvement in task completion time with the asynchronous transmission and are shown graphically in Figure 3.1.

Physician operating the hemostat

We then repeated the experiments with the physician operating one of the hemostats using the teleoperator while the assistant local to the patient operated the second hemostat and the laparoscope. In the synchronous experiments (both video and controller were transmitted together with a 0.6 sec round trip delay) the average completion time was 33.2 seconds. In the asynchronous experiments (the controller signals were transmitted with no time delay while the video signal was sent with a 0.6 sec

round trip delay) we had an average completion time of 20.5 seconds. These experimental results show a 38% improvement in task completion time with the asynchronous transmission and are also shown in Figure 3.1

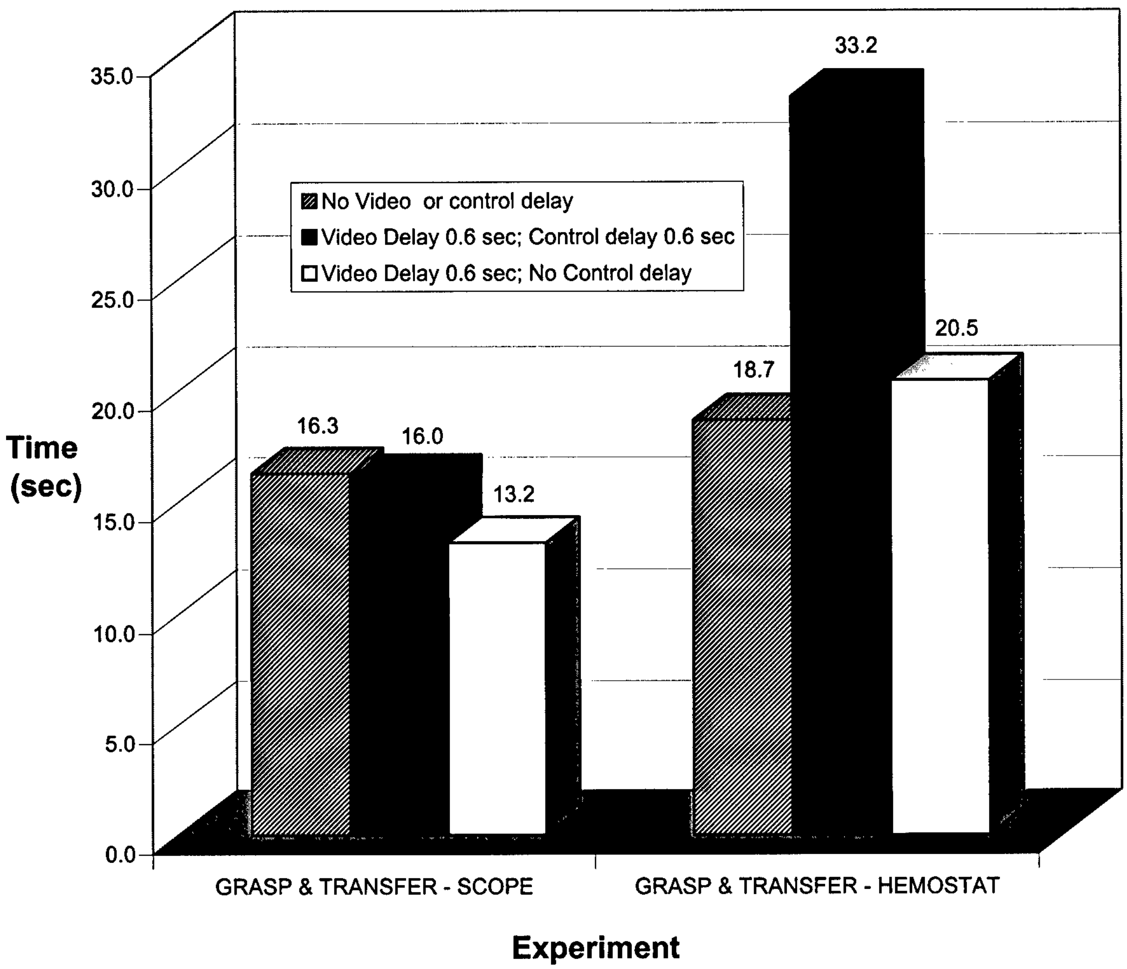

Figure 3.1. Grasp and Transfer Experiments: Performance times for asynchronous and synchronous signals with no transmission time delay

3.1.2 Experiments with a 0.6 second transmission time delay in telemanipulation

In the experiments with a 0.6 second round trip transmission time delay the controller signals were transmitted between teleoperators with a 0.6 delay while the video signals were transmitted with a 1.2 sec round trip delay (0.6 video compression and

decompression time delay plus the 0.6 second transmission time delay). In our first set of experiments we buffered the control signals while the video signal was processed and then sent both video and controller signals simultaneously (synchronous) over the transmission link. In our second set of experiments we immediately sent the control signals over the transmission link without waiting for the video signals (which needed 0.6-sec round trip for the video compression-decompression) which resulted in the asynchronous transmission of video and teleoperator control signals.

Physician operating the laparoscope

In this experiment the physician operated the laparoscope using the teleoperator while the assistant local to the patient operated the two hemostats. In the synchronous experiments (both video and controller were transmitted together with a 1.2 sec round trip delay) the average completion time was 15.1 seconds. In the asynchronous experiments (the controller signals were transmitted with a 0.6 second time delay while the video signal was sent with a 1.2 second round trip delay) we had an average completion time of 14.0 seconds. These experimental results show a 6.4% improvement in task completion time with the asynchronous transmission and are shown graphically in Figure 3.2.

Physician operating the hemostat

We then repeated the experiments with the physician operating one of the hemostats using the teleoperator while the assistant local to the patient operated the second hemostat and the laparoscope. In the synchronous experiments (both video and controller were transmitted together with a 1.2 sec round trip delay) the average completion time was 43.5 seconds. In the asynchronous experiments (the controller signals were transmitted with a 0.6 second time delay while the video signal was sent with a 1.2 second round trip delay) we had an average completion time of 30.1 seconds. These experimental results show a 31% improvement in task completion time with the asynchronous transmission and are shown graphically in Figure 3.2

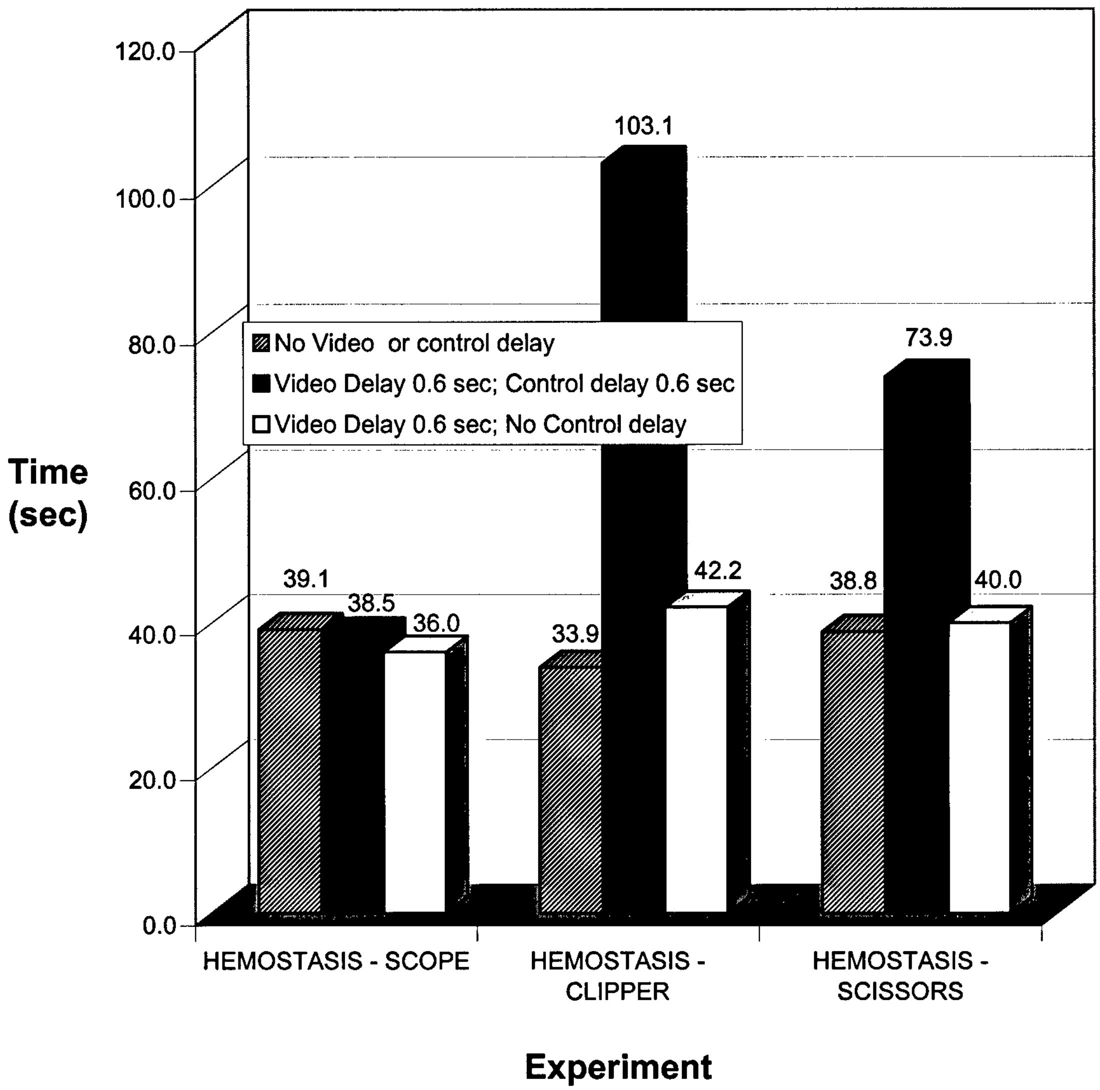

Figure 3.2. Grasp and Transfer Experiments: Performance times for asynchronous and synchronous signals with a 0.6 second transmission time delay

3.2 Hemostasis Experiments

There were three physician / assistant tool combinations for this experiment, a laparoscope, clipper / hemostat, and a scissors. In the first scenario, the physician operated the scope through the teleoperator, while the assistant operated the clipper and the scissors. In the second scenario, the surgeon operated the clipper / hemostat while the assistant operated the laparoscope and the scissors. In the third scenario the physician

operated the scissors while the assistant operated the laparoscope and the clipper. As in our first series of experiments, task completion time is lowest (better performance) when the surgeon operated the laparoscope rather than operating one of the other tools. We found this to be the case in all six experiments in which we varied the time delays for both the video signals and the controller signals.

In our second set of experiments we studied the effect of asynchronous video and control signal transmission on task completion time with various time delays. Our results, which are presented below for each time delay, also showed a significant improvement in task completion time with asynchronous (as compared to synchronous) signal transmission, except when the physician operated the laparoscope.

3.2.1 Experiments with no transmission time delay in telemanipulation

Physician operating the laparoscope

In the synchronous experiments (both video and controller were transmitted together with a 0.6 sec round trip delay) the average completion time was 38.5 seconds. In the asynchronous experiments (the controller signals were transmitted with no time delay while the video signal was sent with a 0.6 sec round trip delay) we had an average completion time of 36.0 seconds. These experimental results show a negligible difference in task completion time between synchronous and asynchronous transmission and are shown graphically in Figure 3.3

Physician operating the hemostat / clipper

In the synchronous experiments (both video and controller were transmitted together with a 0.6 sec round trip delay) the average completion time was 103.1 seconds. In the asynchronous experiments (the controller signals were transmitted with no time delay while the video signal was sent with a 0.6 sec round trip delay) we had an average completion time of 42.2 seconds. These experimental results show a 59% improvement in task completion time with the asynchronous transmission and are shown graphically in Figure 3.3

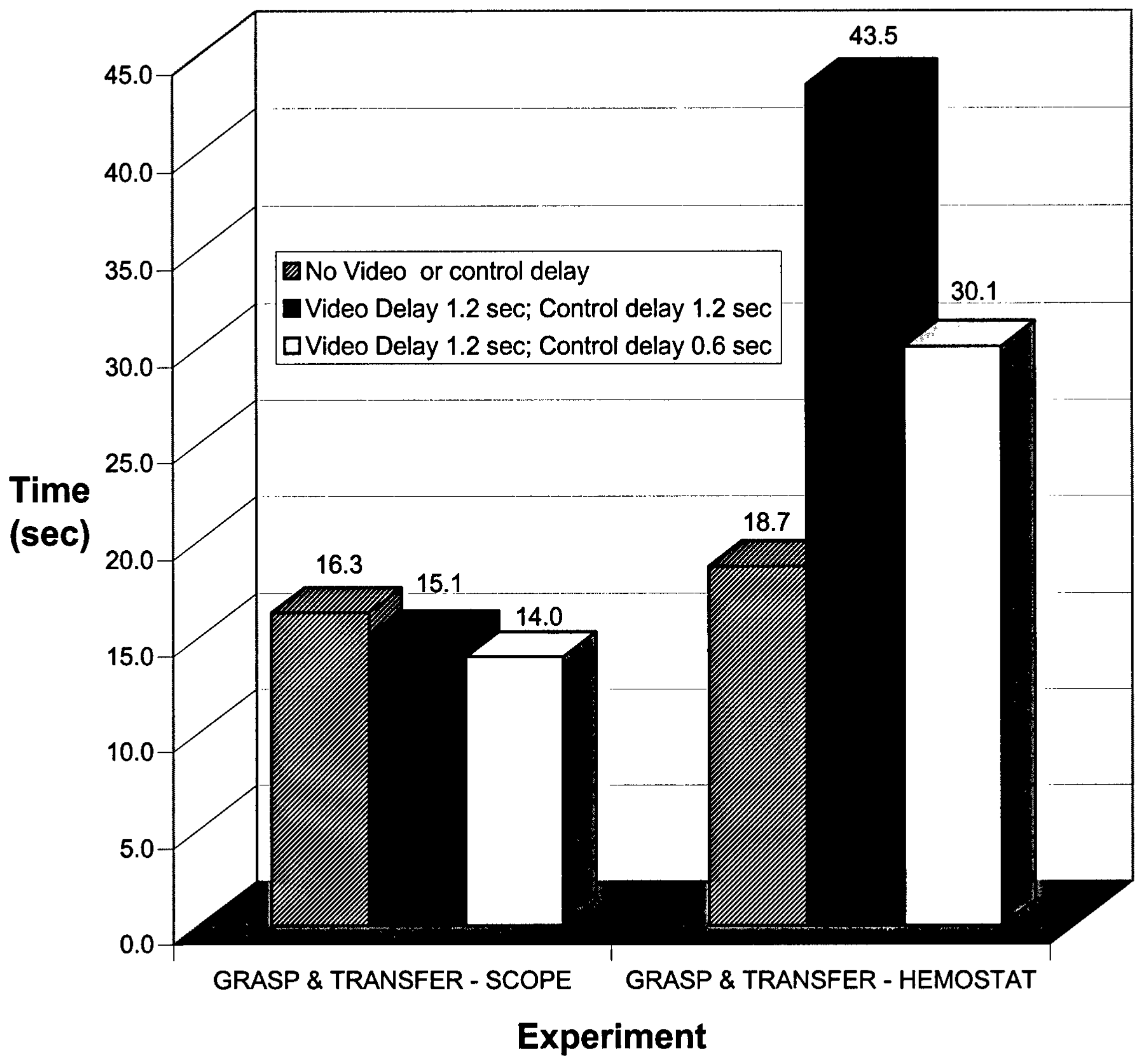

Figure 3.3. Hemostasis Experiments: Performance times for asynchronous and synchronous signals with no transmission time delay

Physician operating the scissors

In the synchronous experiments (both video and controller were transmitted together with a 0.6 sec round trip delay) the average completion time was 73.9 seconds. In the asynchronous experiments (the controller signals were transmitted with no time delay while the video signal was sent with a 0.6 sec round trip delay) we had an average completion time of 40.0 seconds. These experimental results show a 46% improvement

in task completion time with the asynchronous transmission and are shown graphically in Figure 3.3

3.2.2 Experiments with a 0.6 second transmission time delay in telemanipulation

Physician operating the laparoscope

In the synchronous experiments (both video and controller were transmitted together with a 1.2 sec round trip delay) the average completion time was 36.7 seconds. In the asynchronous experiments (the controller signals were transmitted with a 0.6 second time delay while the video signal was sent with a 1.2 second round trip delay) we had an average completion time of 35.9 seconds. As in the no transmission delay case, these experimental results show a negligible difference in task completion time between synchronous and asynchronous transmission and are shown graphically in Figure 3.4

Physician operating the hemostat / clipper

In the synchronous experiments (both video and controller were transmitted together with a 1.2 sec round trip delay) the average completion time was 214.5 seconds. In the asynchronous experiments (the controller signals were transmitted with a 0.6 second time delay while the video signal was sent with a 1.2 second round trip delay) there was an average completion time of 85.4 seconds. These experimental results show a 60% improvement in task completion time with the asynchronous transmission and are shown graphically in Figure 3.4

Physician operating the scissors

In the synchronous experiments (both video and controller were transmitted together with a 1.2 sec round trip delay) the average completion time was 113.4 seconds. In the asynchronous experiments (the controller signals were transmitted with a 0.6 second time delay while the video signal was sent with a 1.2 second round trip delay) we had an average completion time of 57.3 seconds. These experimental results show a 49% improvement in task completion time with the asynchronous transmission and are shown graphically in Figure 3.4

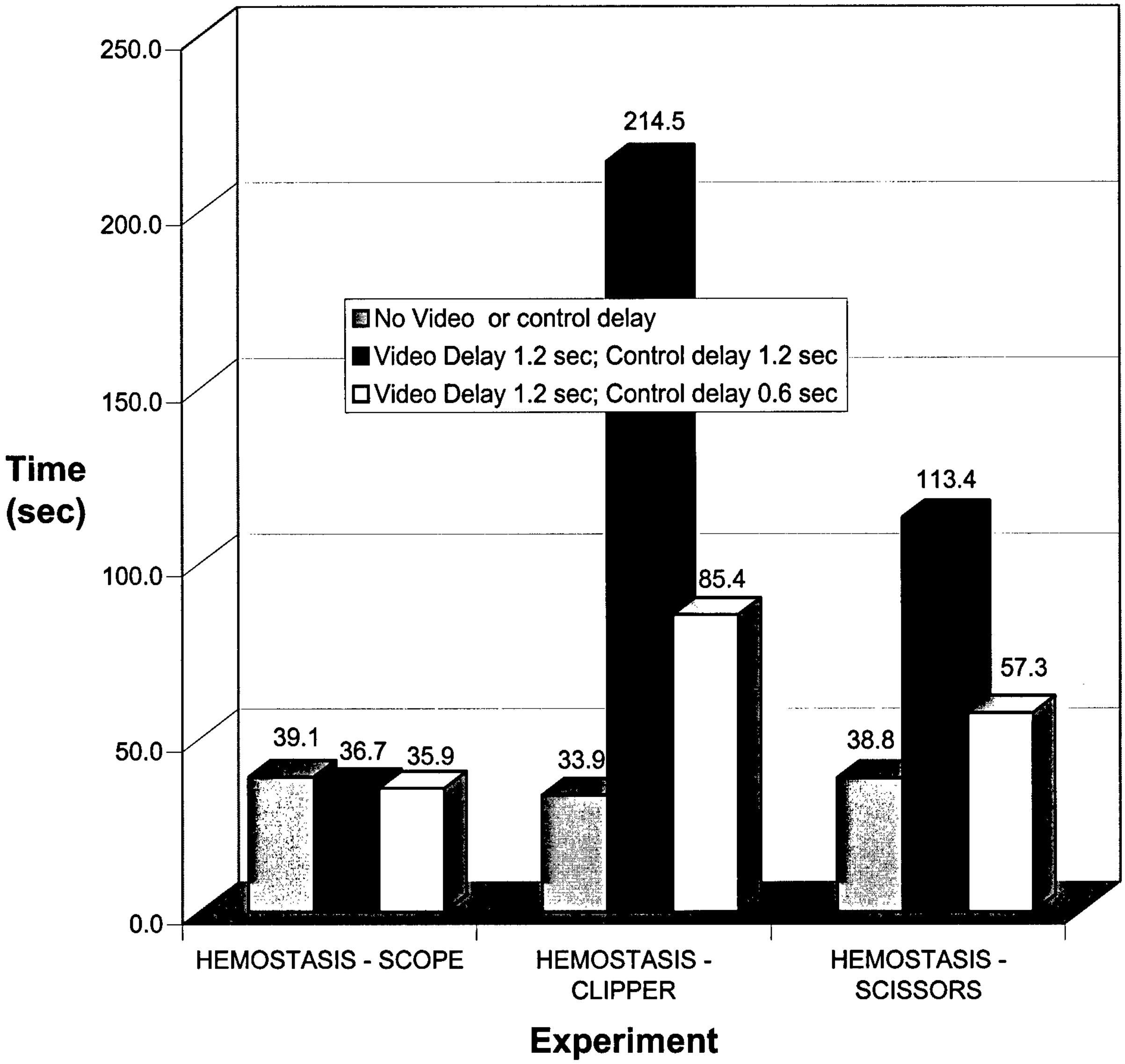

Figure 3.4. Hemostasis Experiments: Performance times for asynchronous and synchronous signals with a 0.6 second transmission time delay

3.3 Discussion

In this second series of experiments in our telesurgery project we attempted to test the hypothesis that sending the signals from a remote telesurgical setup asynchronously (sending the controller signals ahead of the video signals, which were delayed because of

the compression / decompression it required) would improve controller stability and favorably affect task performance by the surgical team.

We had very interesting results. There was essentially no difference in task performance between the synchronous and asynchronous transmission of the telesurgical signals when the physician operated the laparoscope. But we found a significant improvement (31% to 60%) in task completion time when the physician operated any of the laparotomy tools with asynchronous transmission when compared to synchronous transmission.

The result when the physician operated the laparoscope can be easily explained based on control feedback. Degradation in team performance resulting from the effects of time delay (controller instability) is reduced by several factors. First, because the laparoscopic output is an entire field, the person controlling the laparoscope needs to be less sophisticated. Secondly, because the surgeon knows the contents of the surgical field, and what task sequence needed to be performed, he/she is more efficient in minimizing movements (stabilizing field of view) of the laparoscope. In essence, the control of the laparoscope was fairly passive as compared to the operation of the laparoscopic tools.

The significant improvement in task completion time (for asynchronous as contrasted to synchronous transmission) when the surgeon operated the laparoscopic tools was unexpected. Obviously, the advantages of asynchronous transmission more than offset the disadvantage of asynchronous transmission, but this is counter-intuitive. We should separately evaluate the effects of asynchronous transmission and then put the story together to try to explain our results.

The main advantage with asynchronous transmission probably resulted from the increased stability of the telerobotic manipulator because of the decreased time delay that the controller saw. In the case of synchronous transmission (Figure 2.1), since the control signals were sent with the video signals, the controller had an additional delay due to the time it took to compress and then decompress the video signals. The controller delay was

$$T_d = D_c + D + D_d$$

where: T_d is the total delay seen by the controller

D_c is the delay due to video compression

D is the delay due to signal transmission (e.g. phone line)

D_d is the delay due to video decompression

In the case of asynchronous transmission (Figure 2.1), the control signal was sent ahead of the video signal and the controller delay was then:

$$T_d = D$$

where: T_d is the total delay seen by the controller

D is the delay due to signal transmission (e.g. phone line)

So we see that the controller had a smaller time delay in the asynchronous mode, which made it more stable and easier for the physician to operate the tools.

The main disadvantage with asynchronous transmission was that the operator did not receive the force feedback information at the same that he received the video input. The results of our experiments seem to suggest that the improvement in performance because of the more stable controller more than offset the degradation in performance due to the asynchronous force feedback and visual image seen by the physician.

Chapter 4

Conclusions and Future Research

4.1 Conclusions

In this second series of experiments in our telesurgery project we attempted to test the hypothesis that sending the signals from a remote telesurgical setup asynchronously (sending the controller signals as quickly as possible, ahead of the video signals, which are necessarily delayed because of the compression / decompression required) improves controller stability and favorably affects task performance.

There was essentially no difference in task performance between the synchronous and asynchronous transmission of the telesurgical signals when the physician operated the laparoscope and the assistant operated the laparotomy tools. But with asynchronous transmission when compared to synchronous transmission we found a significant improvement (31% to 60%) in task completion time when the physician operated any of the laparotomy tools.

This is an important finding that can be applied to any situation which involves the cooperative actions of an expert operating a remote telemanipulator system (that is limited by bandwidth considerations) and a non-expert person operating some tools at the local site (where the telemanipulator slave is working).

If the expert operating the telemanipulator is using a tool that requires movement or manipulation, then one can improve task completion time if the control signal and the video signals are sent as soon as possible (asynchronous to one another), rather than waiting for the video compression / decompression and then sending the two signals together.

4.2 Future Research

In our series of experiments we varied the time delays, surgical tasks, surgical tools and assistants but kept the surgical expert constant. For our asynchronous experiments, there is the possibility that a different surgical expert might have a problem (or conversely, have an easier time) with the asynchronous force feedback and visual inputs. We suggest that the experiments be repeated with different surgical experts to test this hypothesis.

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Appendices

SUBJECT	STEVE	STEVE	STEVE	STEVE
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	DIRECT	DIRECT	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	NA	NA	0	0
CONTROL TIME DELAY	NA	NA	0	0
DATA	24	18	13	21
	14	41	13	13
	16	16	15	11
	12	15	18	19
	23	17	29	20
	19	11	16	20
	17	9	15	20
	10	18	16	10
	10	15	20	10
	16	14	14	11
	19	13	12	39
	15	12	15	18
MEAN	18.00	16.58	16.33	17.67
VARIANCE	23.60	66.81	20.79	64.79
SUBJECT	STEVE	STEVE	STEVE	STEVE
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0.6	0.6	1.2	1.2
DATA	14	31	14	32
	20	26	18	46
	12	21	18	33
	12	20	18	36
	10	19	10	29
	30	20	20	19
	16	31	10	26
	14	50	12	26
	13	21	9	26
	20	22	8	72
	26	40	14	56
	8	22	6	41
MEAN	16.25	26.92	13.08	36.83
VARIANCE	43.30	92.27	21.36	225.06

SUBJECT	STEVE	STEVE	STEVE	STEVE
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	34	16	16	24
	13	21	17	18
	13	34	13	22
	22	23	10	61
	10	17	19	30
	11	19	17	53
	25	15	12	32
	30	17	13	55
	14	12	16	51
	19	33	17	23
	10	20	8	22
	9	15	13	53
MEAN	17.50	20.17	14.25	37.00
VARIANCE	71.55	47.61	10.75	259.82

SUBJECT	STEVE	STEVE	STEVE	STEVE
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	DIRECT	DIRECT	DIRECT	TELEOPERATOR
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	SCOPE
VIDEO TIME DELAY	NA	NA	NA	0
CONTROL TIME DELAY	NA	NA	NA	0
DATA	62	37	34	37
	65	35	26	44
	48	38	35	63
	76	33	30	30
	40	17		38
MEAN	58.20	32.00	31.25	42.40
VARIANCE	203.20	74.00	16.92	157.30

SUBJECT	STEVE	STEVE	STEVE	STEVE
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	CLIPPER	SCISSORS	SCOPE	CLIPPER
VIDEO TIME DELAY	0	0	0.6	0.6
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	67	40	37	185
	35	56	58	129
	63	31	34	47
	34	26	49	73
	24	35	48	139
MEAN	44.60	37.60	45.20	114.60
VARIANCE	367.30	132.30	94.70	3014.80

SUBJECT	STEVE	STEVE	STEVE	STEVE
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCISSORS	SCOPE	CLIPPER	SCISSORS
VIDEO TIME DELAY	0.6	1.2	1.2	1.2
CONTROL TIME DELAY	0.6	1.2	1.2	1.2
DATA	43	34	377	73
	60	61	277	59
	64	39	351	51
	69	32	266	202
	39	39	162	105
MEAN	55.00	41.00	286.60	98.00
VARIANCE	175.50	134.50	7090.30	3805.00

SUBJECT	STEVE	STEVE	STEVE	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	0.6	0.6	0.6	
CONTROL TIME DELAY	0	0	0	
DATA	35	31	40	
	32	36	31	
	42	18	37	
	39	50	52	
	32	39	27	
MEAN	36.00	34.80	37.40	
VARIANCE	19.50	136.70	92.30	

SUBJECT	STEVE	STEVE	STEVE	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	1.2	1.2	1.2	
CONTROL TIME DELAY	0.6	0.6	0.6	
DATA	42	135	48	
	31	70	50	
	24	88	31	
MEAN	32.33	97.67	43.00	
VARIANCE	82.33	1126.33	109.00	JMT

SUBJECT	BERNARDO	BERNARDO	BERNARDO	BERNARDO
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	DIRECT	DIRECT	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	NA	NA	0	0
CONTROL TIME DELAY	NA	NA	0	0
DATA	24	16	15	21
	15	26	14	17
	30	22	19	19
	18	32	9	48
	21	20	10	14
	12	16	25	14
	19	15	9	40
	30	20	12	28
	11	16	40	20
	22	20	20	15
	18	17	15	32
	13	13	12	20
MEAN	20.00	19.42	16.67	24.00
VARIANCE	42.00	28.27	77.15	118.91

SUBJECT	BERNARDO	BERNARDO	BERNARDO	BERNARDO
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0.6	0.6	1.2	1.2
DATA	10	36	15	67
	13	18	12	36
	12	22	14	36
	17	36	9	22
	23	26	18	25
	11	29	16	36
	14	18	15	33
	10	26	11	67
	15	38	16	43
	12	41	15	69
	22	26	19	39
	16	43	24	24
MEAN	14.58	29.92	15.33	41.42
VARIANCE	18.63	75.17	15.33	289.72

SUBJECT	BERNARDO	BERNARDO	BERNARDO	BERNARDO
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	10	24	19	31
	13	16	20	29
	13	18	15	21
	15	20	21	23
	10	17	13	31
	12	26	10	29
	9	17	12	33
	14	15	13	34
	15	24	15	36
	17	16	14	23
	15	17	12	26
	18	24	10	32
MEAN	13.42	19.50	14.50	29.00
VARIANCE	7.90	15.36	13.73	22.91

SUBJECT	BERNARDO	BERNARDO	BERNARDO	BERNARDO
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	DIRECT	DIRECT	DIRECT	TELEOPERATOR
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	SCOPE
VIDEO TIME DELAY	NA	NA	NA	0
CONTROL TIME DELAY	NA	NA	NA	0
DATA	60	53	42	40
	44	29	34	58
	44	25	32	41
	44	23	33	46
	43	20	35	28
MEAN	47.00	30.00	35.25	42.60
VARIANCE	53.00	176.00	20.92	117.80

SUBJECT	BERNARDO	BERNARDO	BERNARDO	BERNARDO
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	CLIPPER	SCISSORS	SCOPE	CLIPPER
VIDEO TIME DELAY	0	0	0.6	0.6
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	44	36	35	148
	27	38	36	159
	41	29	35	57
	34	39	41	
	60	55	34	
MEAN	41.20	39.40	36.20	121.33
VARIANCE	153.70	91.30	7.70	3134.33

SUBJECT	BERNARDO	BERNARDO	BERNARDO	BERNARDO
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCISSORS	SCOPE	CLIPPER	SCISSORS
VIDEO TIME DELAY	0.6	1.2	1.2	1.2
CONTROL TIME DELAY	0.6	1.2	1.2	1.2
DATA	79	39	96	225
	65	36	166	81
	83	31	180	334
		42		
		40		
MEAN	75.67	37.60	147.33	213.33
VARIANCE	89.33	18.30	2025.33	16104.33

SUBJECT	BERNARDO	BERNARDO	BERNARDO	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	0.6	0.6	0.6	
CONTROL TIME DELAY	0	0	0	
DATA	33	62	50	
	38	40	39	
	28	39	55	
	39			
	37			
MEAN	35.00	47.00	48.00	
VARIANCE	20.50	169.00	67.00	

SUBJECT	BERNARDO	BERNARDO	BERNARDO	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	1.2	1.2	1.2	
CONTROL TIME DELAY	0.6	0.6	0.6	
DATA	41	114	69	
	45	48	61	
	52	87	52	
	75			
	50			
MEAN	46.00	83.00	60.67	
VARIANCE	31.00	1101.00	72.33	JMT

SUBJECT	MIKE	MIKE	MIKE	MIKE
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	DIRECT	DIRECT	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	NA	NA	0	0
CONTROL TIME DELAY	NA	NA	0	0
DATA	23	10	24	41
	19	17	15	22
	17	16	24	45
	11	13	21	28
	40	13	42	25
	19	27	21	30
	19	16	21	28
	16	22	16	26
	22	10	15	20
	14	19	23	16
	22	12	20	18
	15	13		19
MEAN	21.50	15.67	22.00	26.50
VARIANCE	97.50	25.52	55.00	79.36

SUBJECT	MIKE	MIKE	MIKE	MIKE
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0.6	0.6	1.2	1.2
DATA	31	17	14	46
	16	24	15	41
	21	41	24	37
	18	61	25	29
	17	67	33	30
	16	23	18	50
	17	25	10	33
	34	23	13	35
	13	36	21	52
	20	43	8	55
	20	41	20	78
	19	33	13	47
MEAN	20.17	36.17	17.83	44.42
VARIANCE	38.33	241.61	51.06	188.08

SUBJECT	MIKE	MIKE	MIKE	MIKE
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	11	15	13	31
	11	28	25	22
	13	36	14	28
	12	20	25	30
	21	20	22	19
	15	18	32	24
	14	33	21	17
	10	16	18	44
	21	12	20	31
	15	12	16	39
		11	28	47
		49	16	20
MEAN	14.30	22.50	20.83	29.33
VARIANCE	15.34	137.18	34.15	96.06

SUBJECT	MIKE	MIKE	MIKE	MIKE
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	DIRECT	DIRECT	DIRECT	TELEOPERATOR
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	SCOPE
VIDEO TIME DELAY	NA	NA	NA	0
CONTROL TIME DELAY	NA	NA	NA	0
DATA	35	38	46	79
	27	27	41	65
	44	36	33	45
	35	25	35	39
	29	30	32	71
MEAN	34.00	31.20	38.75	59.80
VARIANCE	44.00	31.70	34.92	293.20

SUBJECT	MIKE	MIKE	MIKE	MIKE
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	CLIPPER	SCISSORS	SCOPE	CLIPPER
VIDEO TIME DELAY	0	0	0.6	0.6
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	37	55	46	95
	50	57	36	91
	44	38	38	46
	27	35	30	
	28	63		
MEAN	37.20	49.60	37.50	77.33
VARIANCE	99.70	152.80	43.67	740.33

SUBJECT	MIKE	MIKE	MIKE	MIKE
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCISSORS	SCOPE	CLIPPER	SCISSORS
VIDEO TIME DELAY	0.6	1.2	1.2	1.2
CONTROL TIME DELAY	0.6	1.2	1.2	1.2
DATA	69	38	148	140
	45	32	177	47
	83	57	441	76
	60	31		
	69	31		
MEAN	65.20	37.80	255.33	87.67
VARIANCE	195.20	123.70	26064.33	2264.33

SUBJECT	MIKE	MIKE	MIKE	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	0.6	0.6	0.6	
CONTROL TIME DELAY	0	0	0	
DATA	47	45	52	
	35	25	25	
	37	29	37	
	41			
	38			
MEAN	39.60	33.00	38.00	
VARIANCE	21.80	112.00	183.00	

SUBJECT	MIKE	MIKE	MIKE	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	1.2	1.2	1.2	
CONTROL TIME DELAY	0.6	0.6	0.6	
DATA	37	110	57	
	45	73	51	
	48	140	40	
	39			
	35			
MEAN	43.33	107.67	49.33	
VARIANCE	32.33	1126.33	74.33	JMT

SUBJECT	SUYEONG	SUYEONG	SUYEONG	SUYEONG
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	DIRECT	DIRECT	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	NA	NA	0	0
CONTROL TIME DELAY	NA	NA	0	0
DATA	24	16	15	12
	25	13	24	22
	18	19	9	16
	19	35	12	17
	33	10	11	18
	17	8	9	9
	13	11	10	16
	27	7	13	20
	24	11	16	21
	17	17	19	22
	11	17	11	13
	8	15	6	11
MEAN	22.67	14.92	12.92	16.42
VARIANCE	36.27	54.45	24.45	19.54
SUBJECT	SUYEONG	SUYEONG	SUYEONG	SUYEONG
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0.6	0.6	1.2	1.2
DATA	14	28	14	43
	16	26	15	27
	12	28	13	60
	19	62	17	33
	13	24	16	26
	17	38	18	47
	15	56	11	57
	24	41	14	58
	15	103	10	37
	22	30	17	48
	29	39	11	34
	11	41	13	46
MEAN	17.25	43.00	14.08	43.00
VARIANCE	28.75	495.27	6.81	138.36

SUBJECT	SUYEONG	SUYEONG	SUYEONG	SUYEONG
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	14	19	13	22
	11	18	20	26
	13	15	15	19
	12	20	9	19
	12	21	10	20
	10	16	8	23
	8	16	7	22
	16	23	9	27
	15	28	16	32
	13	27	18	22
	9	14	8	48
	8	17	7	28
MEAN	11.75	19.50	11.67	25.67
VARIANCE	6.93	20.64	20.79	64.97

SUBJECT	SUYEONG	SUYEONG	SUYEONG	SUYEONG
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	DIRECT	DIRECT	DIRECT	TELEOPERATOR
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	SCOPE
VIDEO TIME DELAY	NA	NA	NA	0
CONTROL TIME DELAY	NA	NA	NA	0
DATA	46	40	24	32
	47	34	35	41
	48	25	28	38
	38	21	39	32
	28	22	41	26
MEAN	41.40	28.40	31.50	33.80
VARIANCE	71.80	68.30	45.67	34.20

SUBJECT	SUYEONG	SUYEONG	SUYEONG	SUYEONG
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	CLIPPER	SCISSORS	SCOPE	CLIPPER
VIDEO TIME DELAY	0	0	0.6	0.6
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	27	63	51	135
	22	32	53	117
	54	39	65	99
	21	31	35	
	19	42	39	
MEAN	28.60	41.40	48.60	117.00
VARIANCE	210.30	167.30	142.80	324.00

SUBJECT	SUYEONG	SUYEONG	SUYEONG	SUYEONG
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCISSORS	SCOPE	CLIPPER	SCISSORS
VIDEO TIME DELAY	0.6	1.2	1.2	1.2
CONTROL TIME DELAY	0.6	1.2	1.2	1.2
DATA	63	43	144	89
	43	39	121	100
	69	32	78	67
		38		
		37		
MEAN	58.33	37.80	114.33	85.33
VARIANCE	185.33	15.70	1122.33	282.33

SUBJECT	SUYEONG	SUYEONG	SUYEONG	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	0.6	0.6	0.6	
CONTROL TIME DELAY	0	0	0	
DATA	55	71	48	
	39	23	51	
	41	43	34	
	32			
	36			
MEAN	40.60	45.67	44.33	
VARIANCE	76.30	581.33	82.33	
SUBJECT	SUYEONG	SUYEONG	SUYEONG	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	1.2	1.2	1.2	
CONTROL TIME DELAY	0.6	0.6	0.6	
DATA	40	71	63	
	39	60	62	
	36	85	49	
	37			
MEAN	38.33	72.00	58.00	
VARIANCE	4.33	157.00	61.00	JMT

SUBJECT	NICK	NICK	NICK	NICK
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	DIRECT	DIRECT	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	NA	NA	0	0
CONTROL TIME DELAY	NA	NA	0	0
DATA	8	22	15	15
	25	12	9	25
	9	12	8	14
	9	10	11	16
	8	11	10	13
	7	7	13	21
	9	9	7	23
	7	19	6	13
	12	35	10	11
	11	11	8	32
	9	9	18	16
	10	13	10	17
MEAN	11.00	14.17	10.42	18.00
VARIANCE	47.60	61.06	11.90	37.45

SUBJECT	NICK	NICK	NICK	NICK
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0.6	0.6	1.2	1.2
DATA	15	31	7	32
	14	19	10	28
	11	22	7	23
	19	15	7	23
	10	31	11	23
	6	21	6	43
	8	22	7	165
	12	60	24	38
	8	31	13	38
	7	39	10	100
	6	75	11	51
	8	55	7	31
MEAN	10.33	35.08	10.00	49.58
VARIANCE	16.24	352.63	24.36	1765.17

SUBJECT	NICK	NICK	NICK	NICK
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	12	22	8	24
	7	18	12	22
	7	21	15	17
	16	23	10	23
	11	21	7	19
	7	14	7	21
	7	19	10	11
	11	19	7	20
	20	12	8	17
	6	11	8	28
	15	13	6	67
	10	13	6	46
MEAN	10.75	17.17	8.67	26.25
VARIANCE	19.30	18.52	7.15	237.30

SUBJECT	NICK	NICK	NICK	NICK
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	DIRECT	DIRECT	DIRECT	TELEOPERATOR
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	SCOPE
VIDEO TIME DELAY	NA	NA	NA	0
CONTROL TIME DELAY	NA	NA	NA	0
DATA	48	14	68	34
	35	16	57	17
	33	21	27	23
	24	20	30	19
	26	20	36	25
MEAN	33.20	18.20	45.50	23.60
VARIANCE	89.70	9.20	407.00	43.80

SUBJECT	NICK	NICK	NICK	NICK
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	CLIPPER	SCISSORS	SCOPE	CLIPPER
VIDEO TIME DELAY	0	0	0.6	0.6
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	29	37	38	111
	14	27	40	63
	37	26	26	71
	29	31	17	
	31	19	18	
MEAN	28.00	28.00	27.80	81.67
VARIANCE	72.00	44.00	117.20	661.33

SUBJECT	NICK	NICK	NICK	NICK
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCISSORS	SCOPE	CLIPPER	SCISSORS
VIDEO TIME DELAY	0.6	1.2	1.2	1.2
CONTROL TIME DELAY	0.6	1.2	1.2	1.2
DATA	113	33	584	60
	125	33	151	80
	83	42	165	60
		28		
		27		
MEAN	107.00	32.60	300.00	66.67
VARIANCE	468.00	35.30	60541.00	133.33

SUBJECT	NICK	NICK	NICK	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	0.6	0.6	0.6	
CONTROL TIME DELAY	0	0	0	
DATA	34	50	48	
	32	30	27	
	26	63	23	
	24			
	21			
MEAN	27.40	47.67	32.67	
VARIANCE	29.80	276.33	180.33	

SUBJECT	NICK	NICK	NICK	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	1.2	1.2	1.2	
CONTROL TIME DELAY	0.6	0.6	0.6	
DATA	25	110	61	
	17	52	75	
	21	42	58	
	29			
	15			
MEAN	21.00	68.00	64.67	
VARIANCE	16.00	1348.00	82.33	JMT

SUBJECT	JAY	JAY	JAY	JAY
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	DIRECT	DIRECT	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	NA	NA	0	0
CONTROL TIME DELAY	NA	NA	0	0
DATA	34	14	24	19
	23	25	14	20
	32	13	10	36
	15	10	10	10
	15	20	10	31
	24	7	11	14
	36	13	22	17
	25	10	38	9
	16	11	29	11
	13	24	14	13
	12	10	13	14
	12	8	36	11
MEAN	23.83	13.75	19.25	17.08
VARIANCE	65.37	36.39	106.93	71.72
SUBJECT	JAY	JAY	JAY	JAY
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0.6	0.6	1.2	1.2
DATA	19	45	10	32
	12	30	26	41
	18	27	19	50
	15	22	14	30
	19	26	48	32
	12	29	16	29
	21	27	10	59
	26	29	30	39
	14	30	11	42
	8	18	36	46
	17	33	10	104
	28	23	12	44
MEAN	17.42	28.25	20.17	45.67
VARIANCE	33.54	44.57	152.15	416.24

SUBJECT	JAY	JAY	JAY	JAY
EXPERIMENT	HEMOSTAT	HEMOSTAT	HEMOSTAT	HEMOSTAT
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCOPE	HEMOSTAT	SCOPE	HEMOSTAT
VIDEO TIME DELAY	0.6	0.6	1.2	1.2
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	10	20	10	20
	10	15	11	25
	10	12	11	19
	13	14	9	18
	6	14	17	25
	27	19	34	55
	17	12	11	41
	8	46	18	41
	8	20	11	18
	13	33	11	27
	7	48	13	43
	11	36	10	65
MEAN	11.67	24.08	13.83	33.08
VARIANCE	32.42	173.72	47.97	246.81

SUBJECT	JAY	JAY	JAY	JAY
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	DIRECT	DIRECT	DIRECT	TELEOPERATOR
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	SCOPE
VIDEO TIME DELAY	NA	NA	NA	0
CONTROL TIME DELAY	NA	NA	NA	0
DATA	32	29	37	28
	28	30	38	34
	32	20	62	34
	36	20	33	29
	30	16	28	36
MEAN	31.60	23.00	42.50	32.20
VARIANCE	8.80	38.00	173.67	12.20

SUBJECT	JAY	JAY	JAY	JAY
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	CLIPPER	SCISSORS	SCOPE	CLIPPER
VIDEO TIME DELAY	0	0	0.6	0.6
CONTROL TIME DELAY	0	0	0.6	0.6
DATA	20	32	46	129
	21	51	29	107
	18	31	29	84
	27	42	35	
	32	29	38	
MEAN	23.60	37.00	35.40	106.67
VARIANCE	33.30	86.50	50.30	506.33

SUBJECT	JAY	JAY	JAY	JAY
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR
SURGEON OPERATES	SCISSORS	SCOPE	CLIPPER	SCISSORS
VIDEO TIME DELAY	0.6	1.2	1.2	1.2
CONTROL TIME DELAY	0.6	1.2	1.2	1.2
DATA	119	38	205	199
	60	33	245	58
	68	35	101	132
		36		
		26		
MEAN	82.33	33.60	183.67	129.67
VARIANCE	1024.33	21.30	5525.33	4974.33

SUBJECT	JAY	JAY	JAY	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	0.6	0.6	0.6	
CONTROL TIME DELAY	0	0	0	
DATA	43	55	47	
	25	36	34	
	37	44	37	
	54			
	29			
MEAN	37.60	45.00	39.33	
VARIANCE	6.20	9.00	9.80	
SUBJECT	JAY	JAY	JAY	
EXPERIMENT	HEMOSTASIS	HEMOSTASIS	HEMOSTASIS	
CONDITION	TELEOPERATOR	TELEOPERATOR	TELEOPERATOR	
SURGEON OPERATES	SCOPE	CLIPPER	SCISSORS	
VIDEO TIME DELAY	1.2	1.2	1.2	
CONTROL TIME DELAY	0.6	0.6	0.6	
DATA	40	107	42	
	33	59	95	
	31	87	68	
	25			
	34			
MEAN	34.67	84.33	68.33	
VARIANCE	22.33	581.33	702.33	JMT